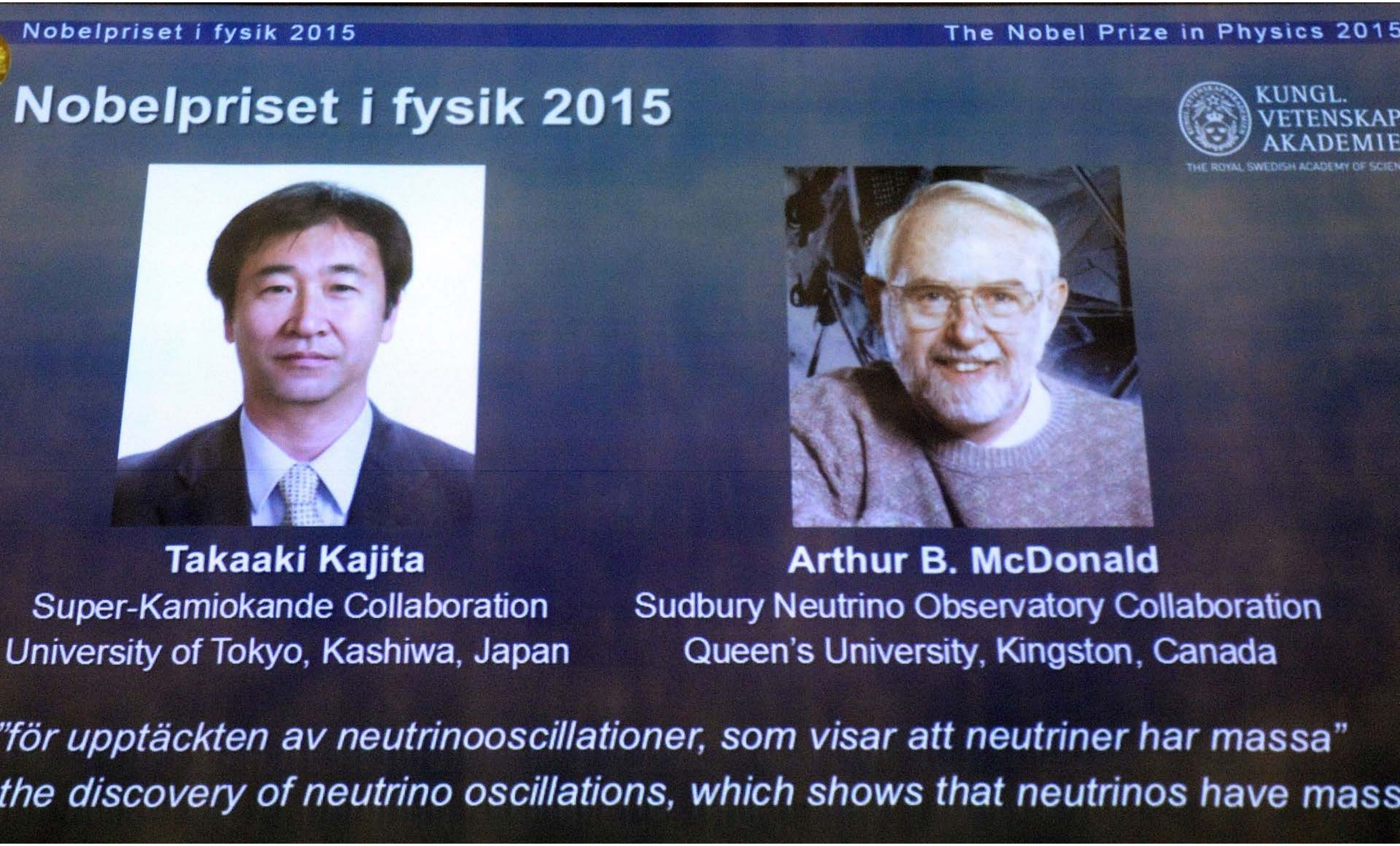
WIMP searches with liquid Xe and liquid Ar

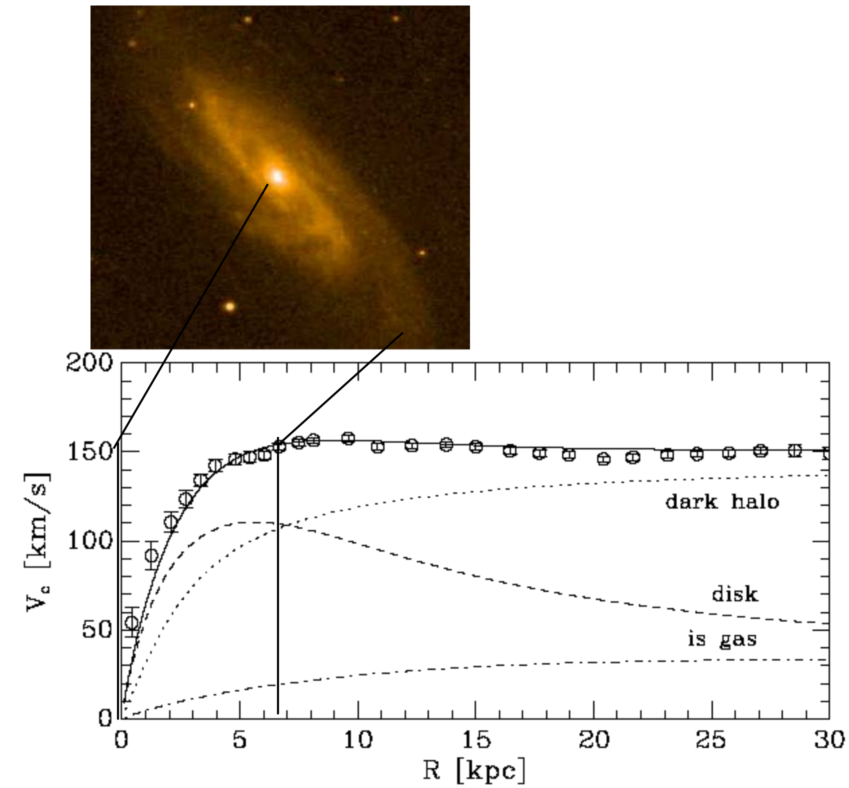
T. Shutt
SLAC

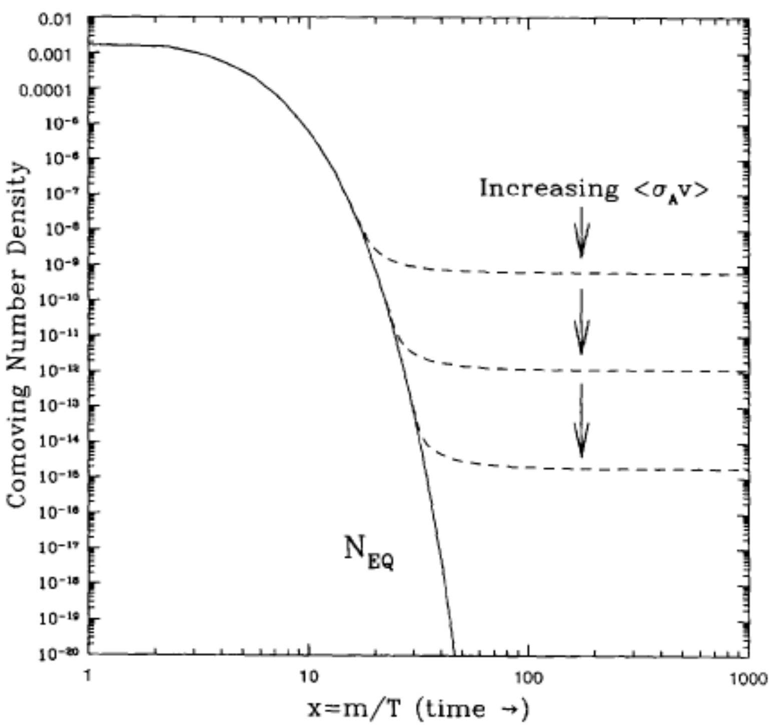
Physics Noble Prize - 2015



Dark Matter

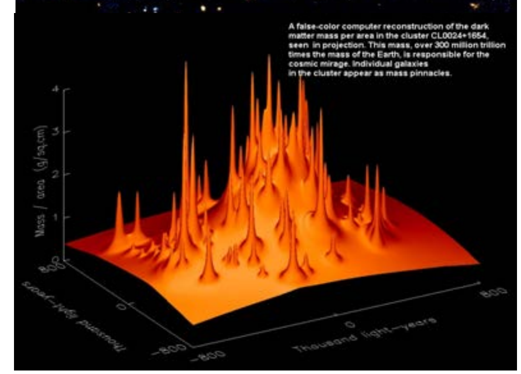
- Dark Matter:
  - Galactic rotation curves
  - Galaxy clusters
  - BBN
  - CMB
  - Structure evolution





Q: Why GeV-TeV masses?

A: Freezeout suggests the weak scale.



Direct DM detection

- Galactic "Halo" of dark matter

$$\rho \sim 300\ \mathrm{m_{proton}}/\mathrm{liter}$$

- Velocities: $\beta \sim 10^{-3}$

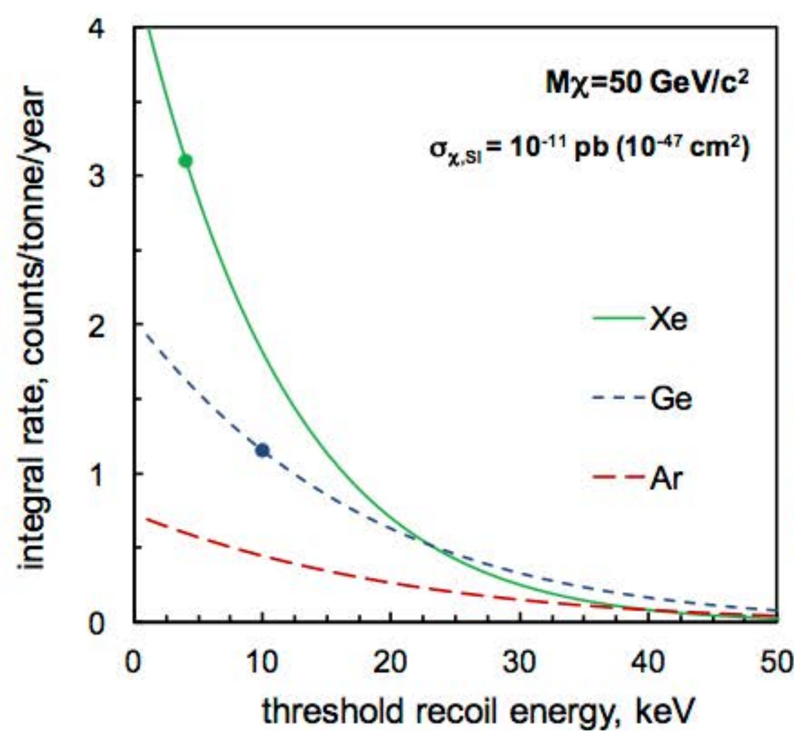
- Scattering on nuclei.

$$E \sim M\beta^2 \sim \mathrm{keV}$$

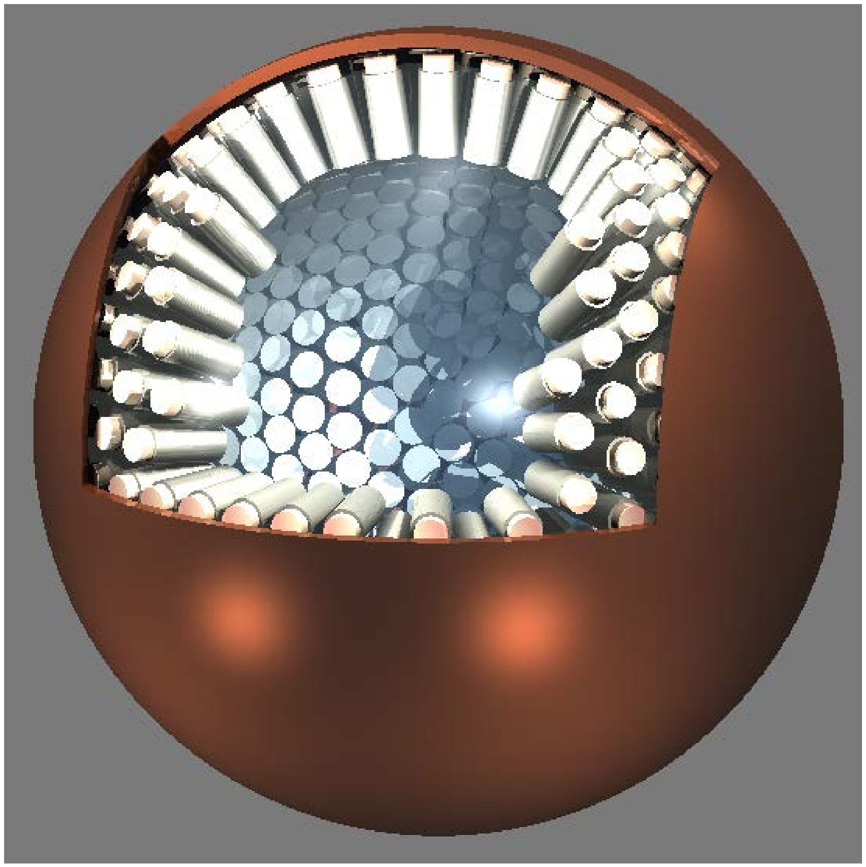
$$\lambda = \frac{h}{mv} \sim R_{nucleus}$$

$$\sigma \propto A^2$$

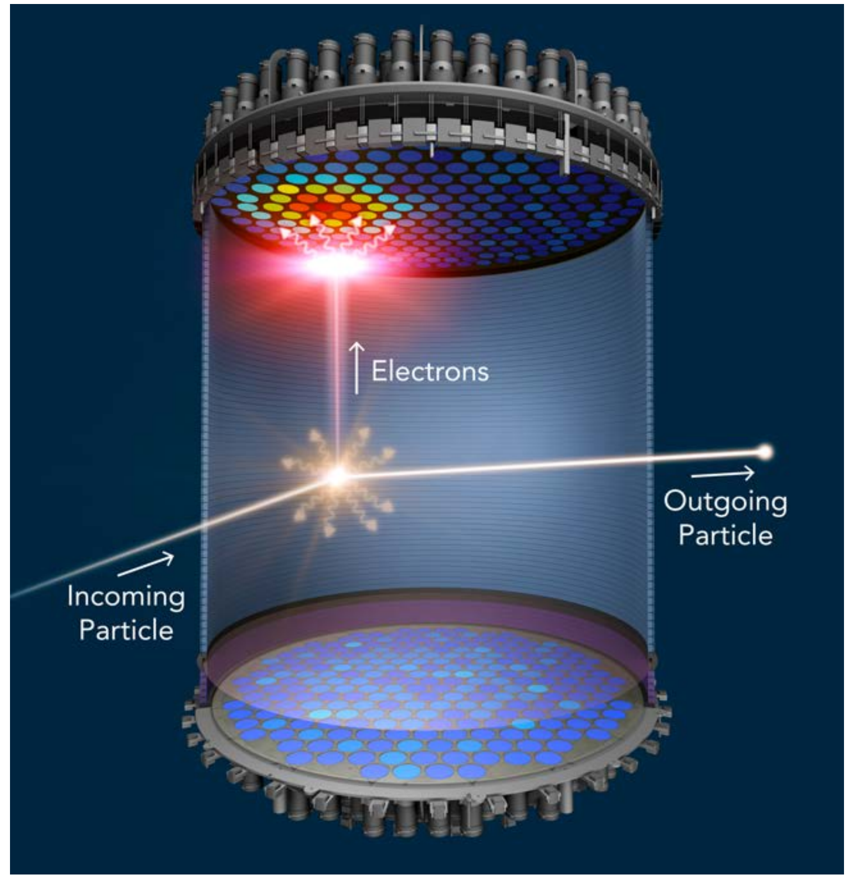
- Rate < ~0.3 events / 100 kg / month



Single phase / Dual phase



4π Scintillation



Time Projection Chambers (TPC)

Why liquid nobles?

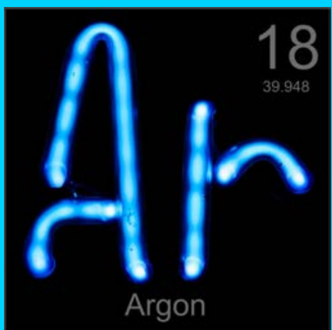
- Large mass

- Good detector media: scintillation + charge

- Pure, hence radiopure*

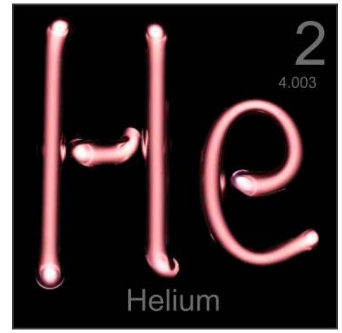
*except when not: ^{39}Ar, ^{85}Kr

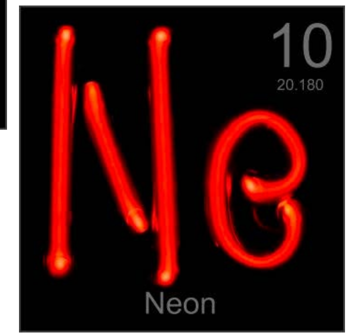
Liquid Nobles



Single Phase — **DEAP**, **MiniCLEAN**

Dual Phase — **DarkSide**, **ArDM**





Light WIMPs
D. McKinsey talk

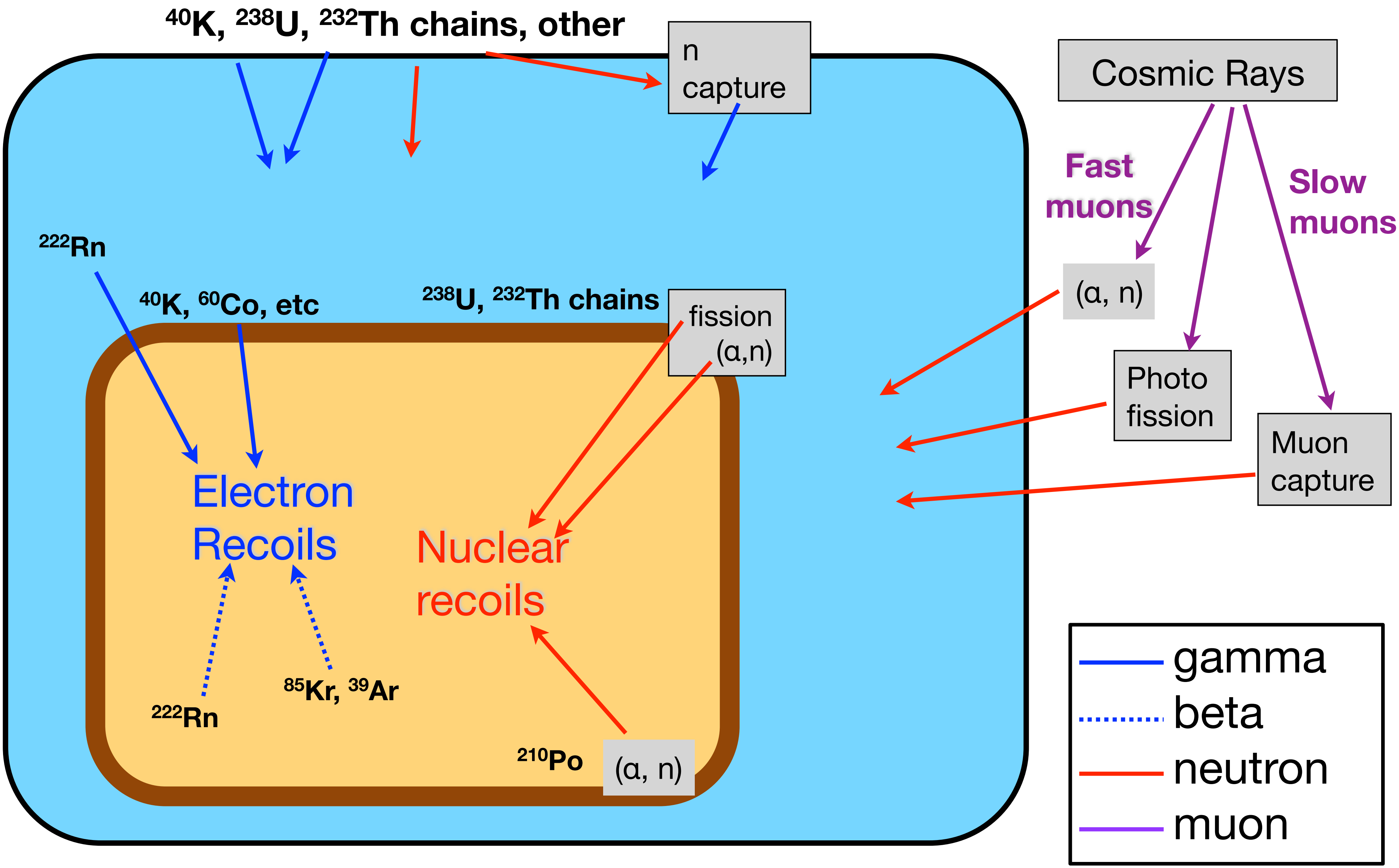
Single Phase — **XMASS**

Dual Phase — **LUX/LZ**, **XENON-100/1T/nT**, **Panda-X**

1 MBq/kg

discharge tubes from
http://periodictable.com

Backgrounds: natural radioactivity and cosmic rays



Ambient backgrounds: 10^{11} time DM rate

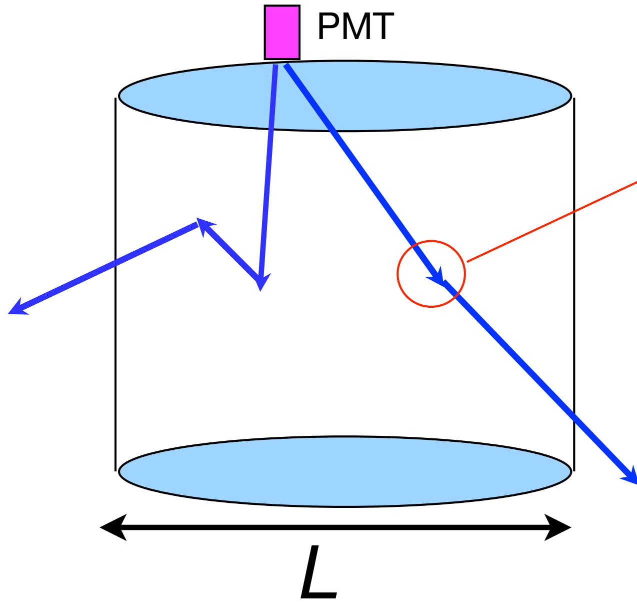
Powerful self shielding

Gammas, neutrons
λ ~10 cm

Penetration probability

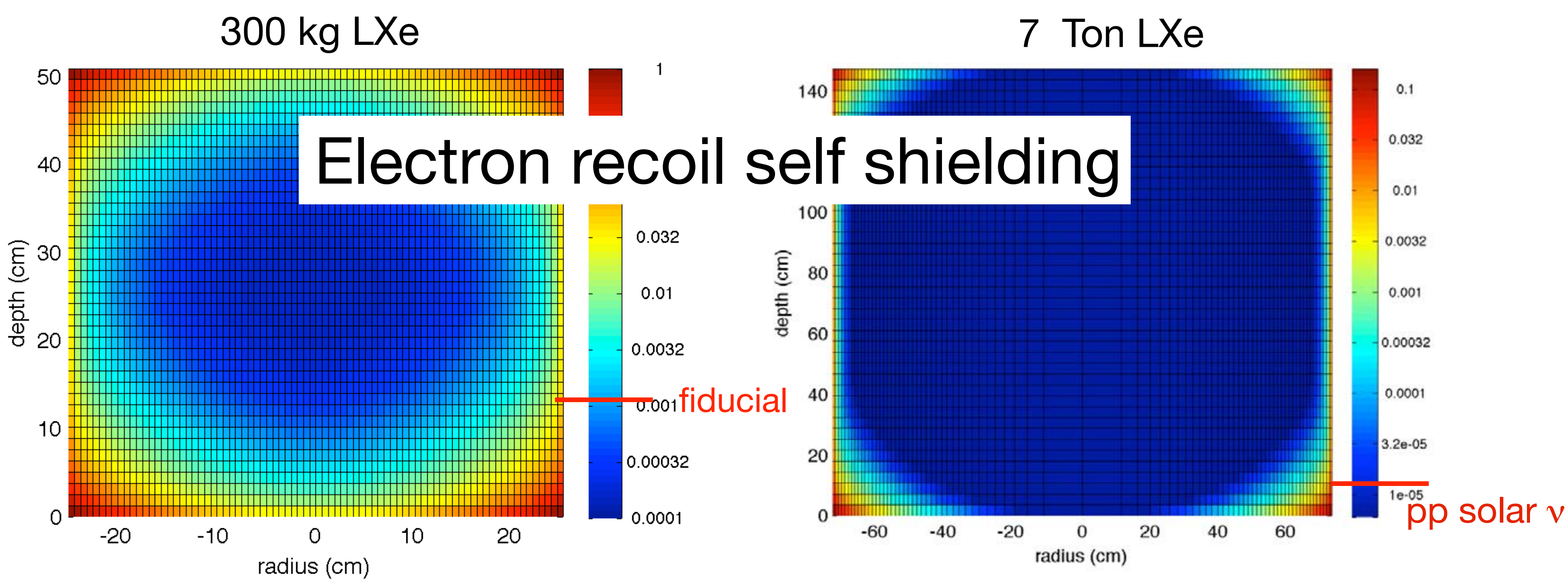
$$P(x) = e^{(-\frac{x}{\lambda})}$$

Neutrons, *ßß γ* bkgnd.

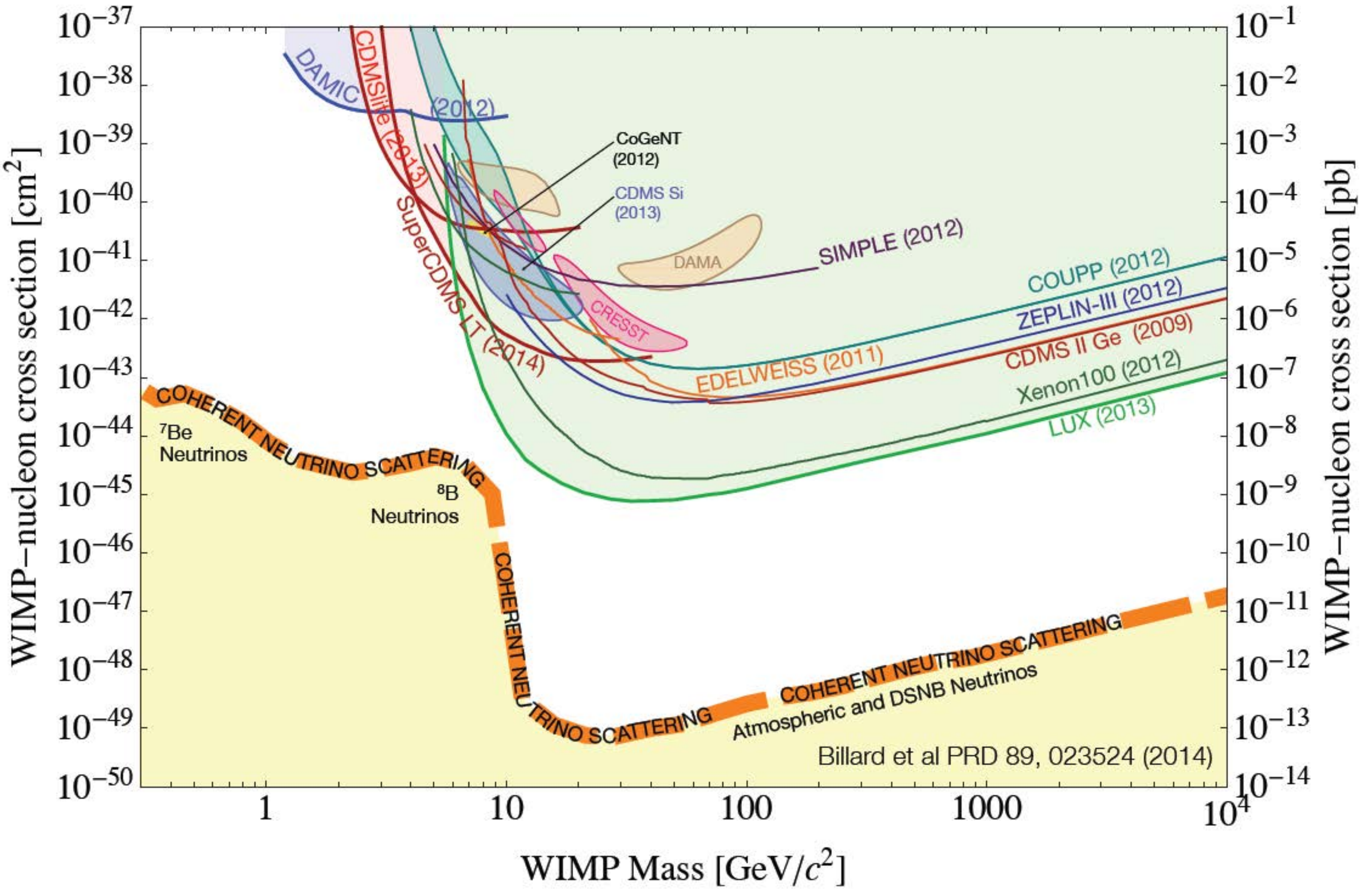


DM ER background:
Single, low-energy
Compton scatter

$$P \cong \frac{L}{\lambda} e^{(-\frac{L}{\lambda})}$$

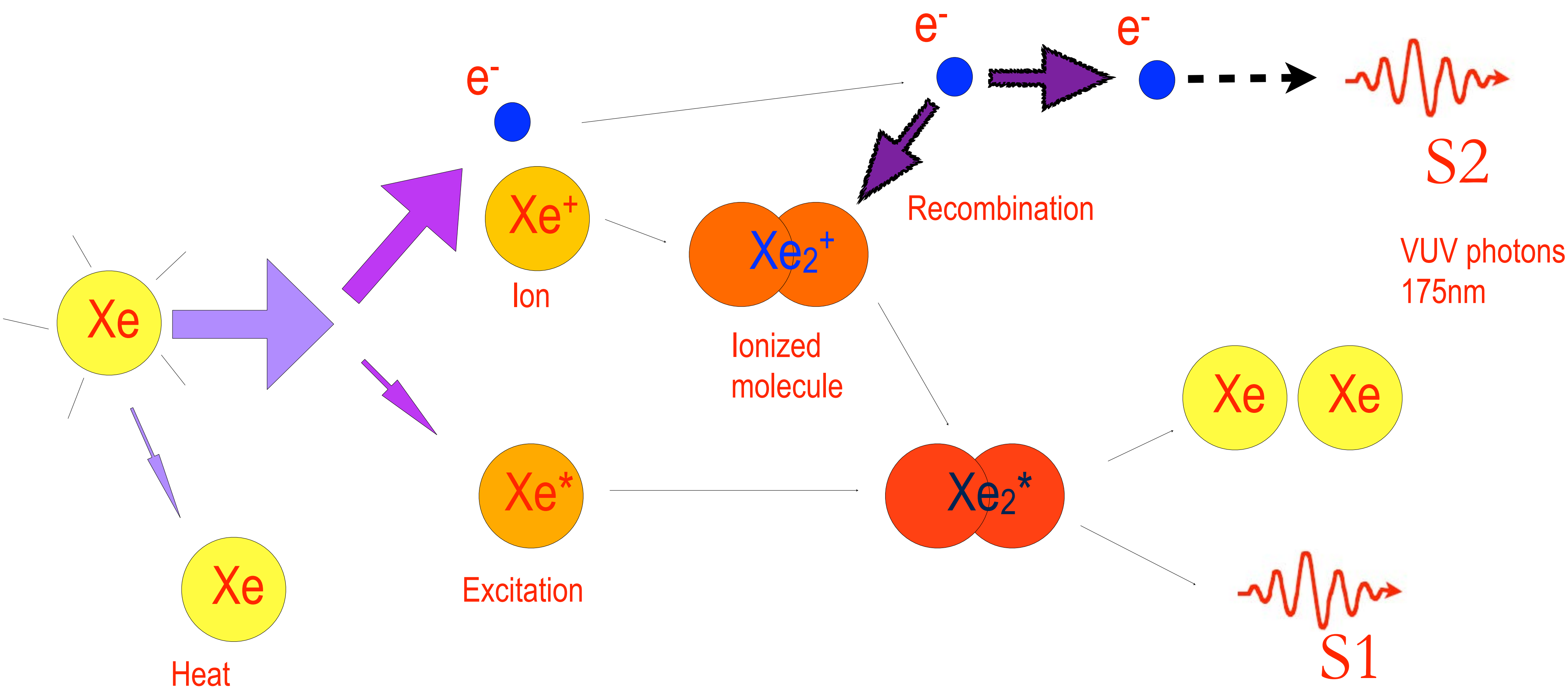


The current picture



Signal production in liquid nobles

Electron recoil

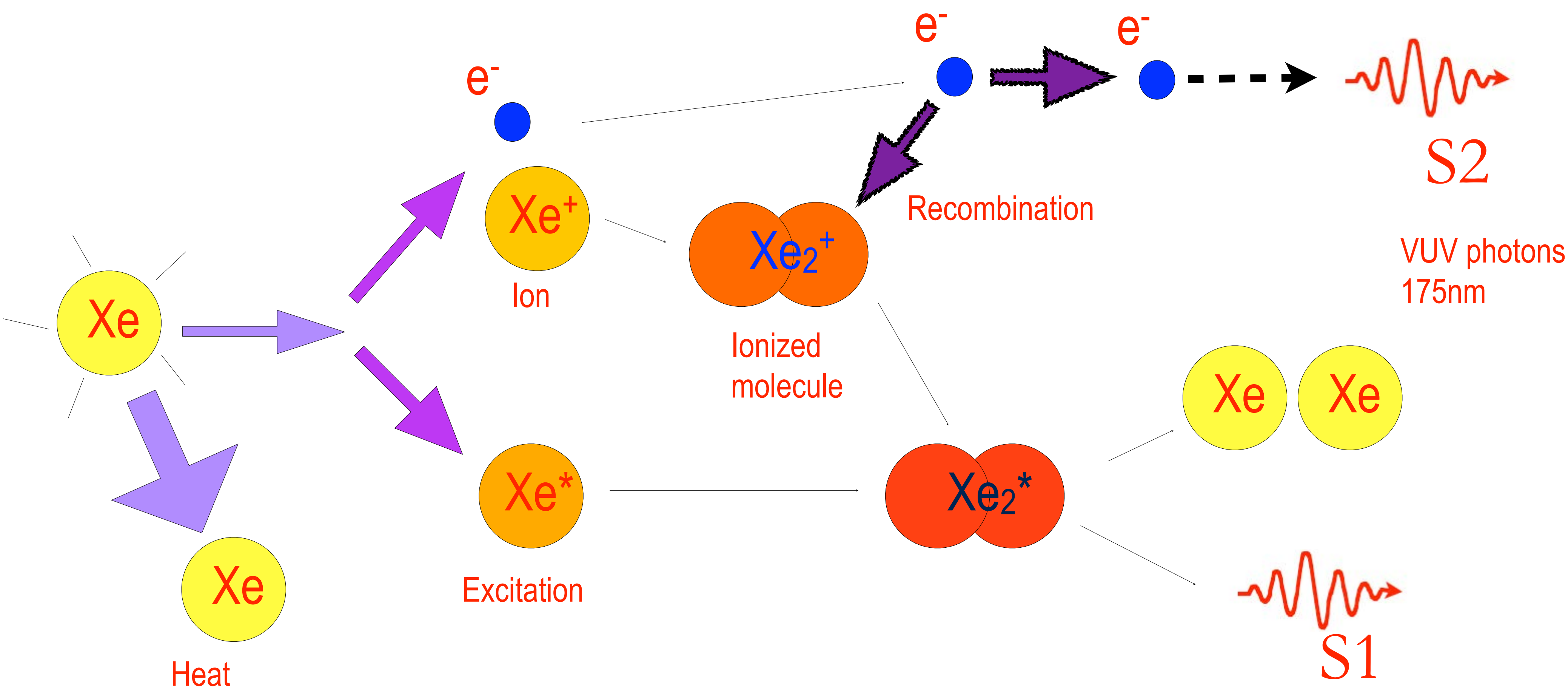


Branching ( ) sketched for **electron** recoils

diagram - T. Shutt

Signal production in liquid nobles

Nuclear recoil

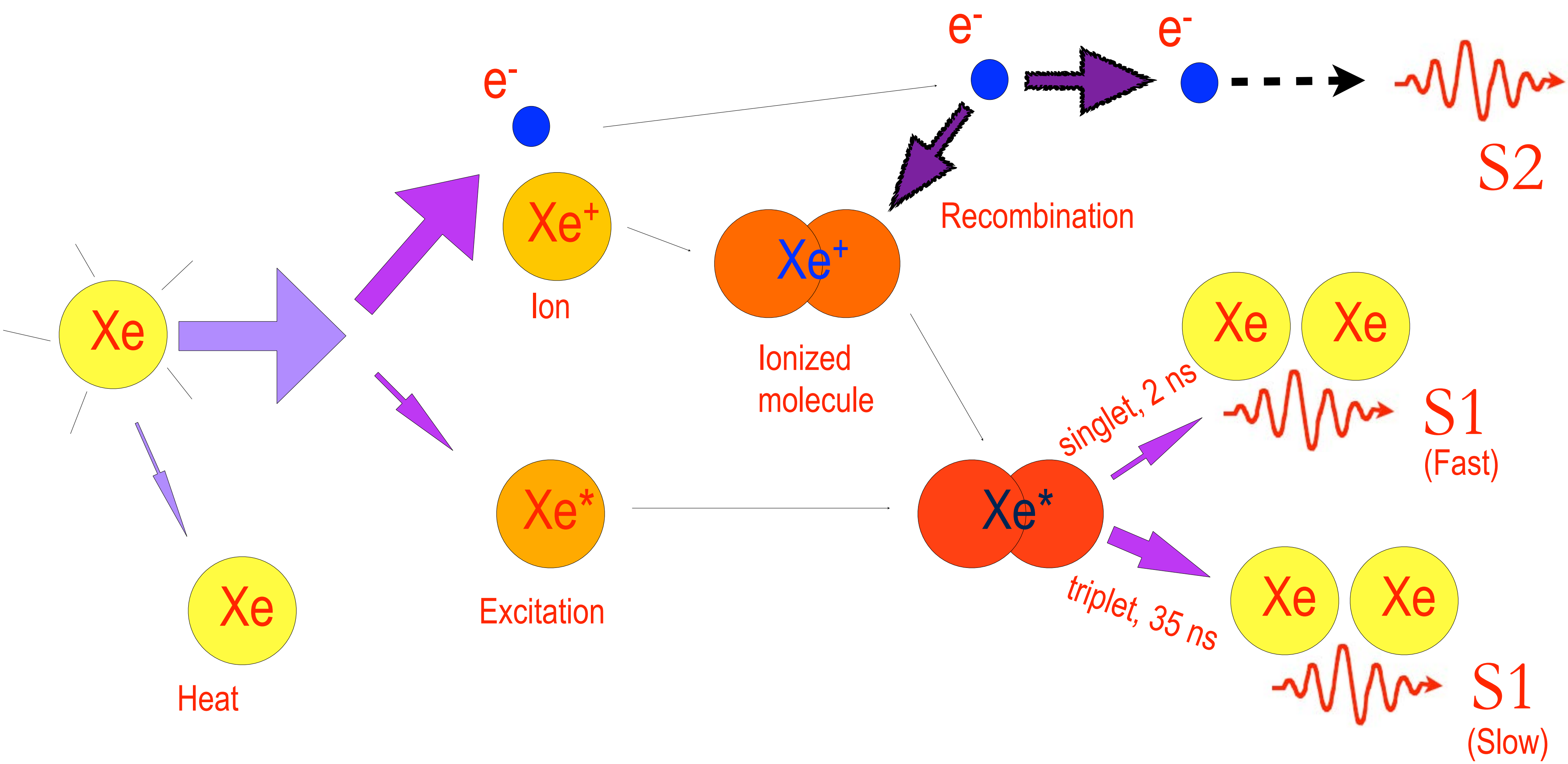


Branching (→) sketched for **nuclear** recoils

diagram - T. Shutt

Signal production in liquid nobles

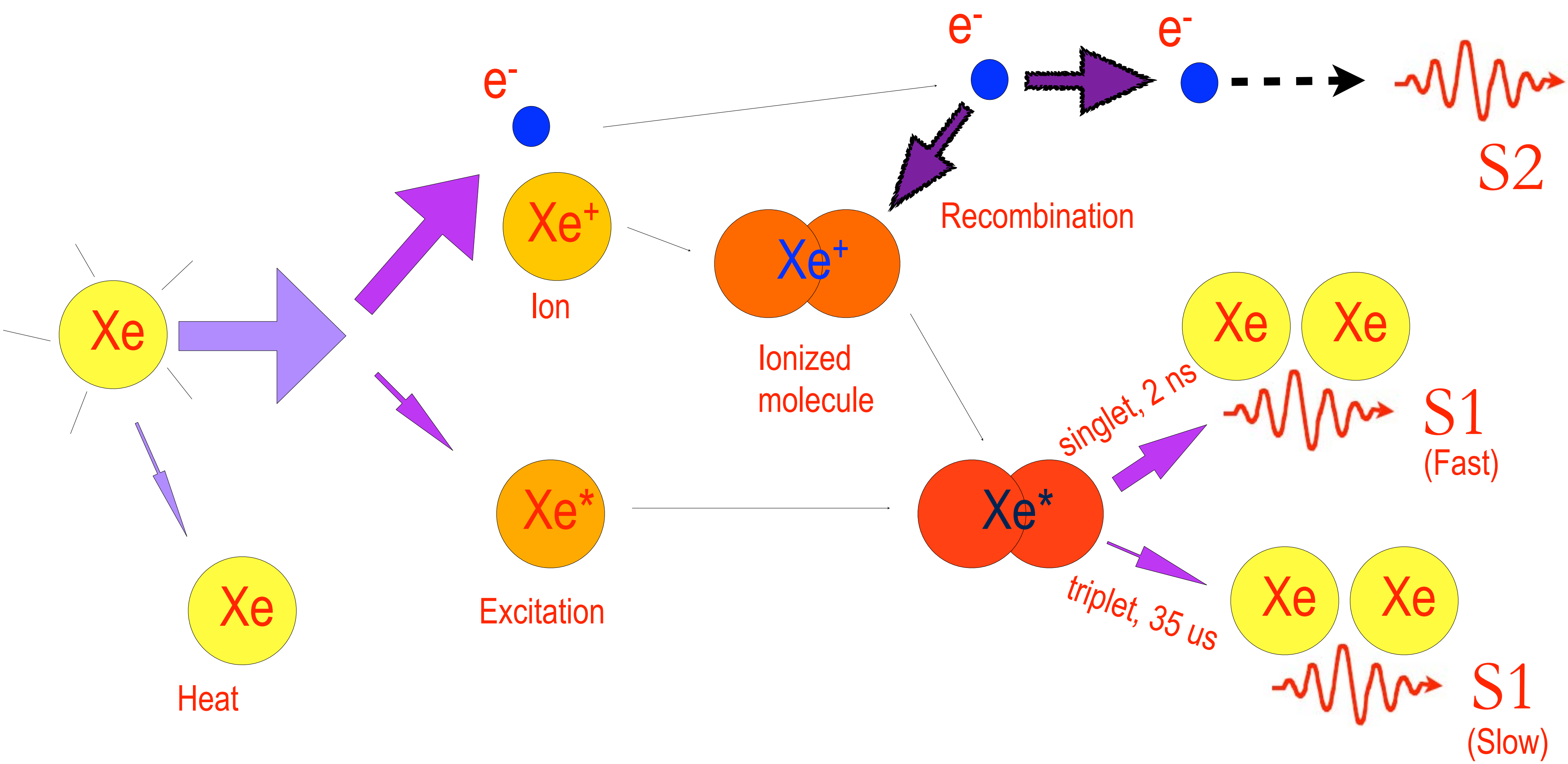
Electron recoil



Branching (→) sketched for **electron** recoils

Signal production in liquid nobles

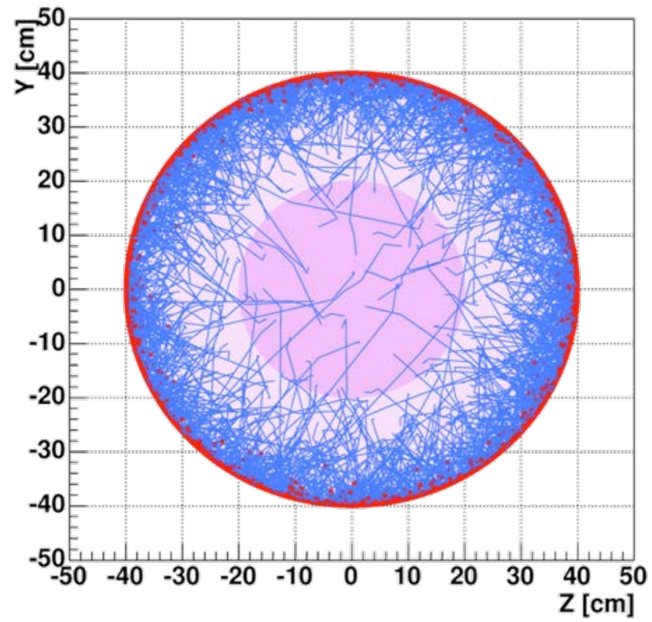
Electron recoil

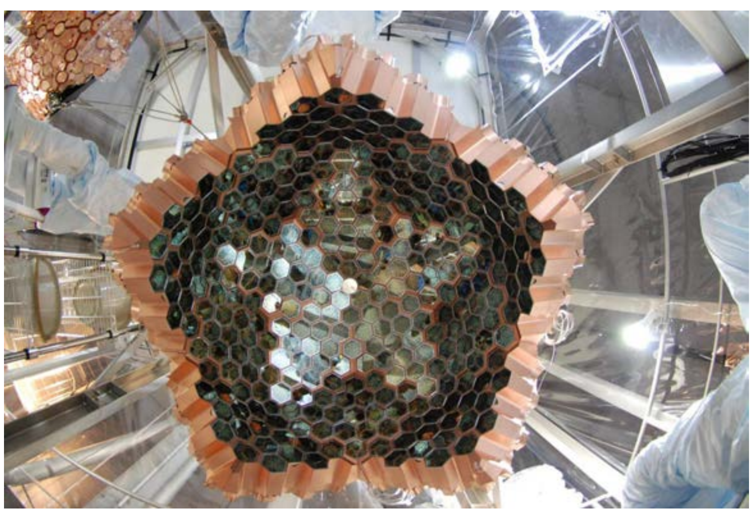


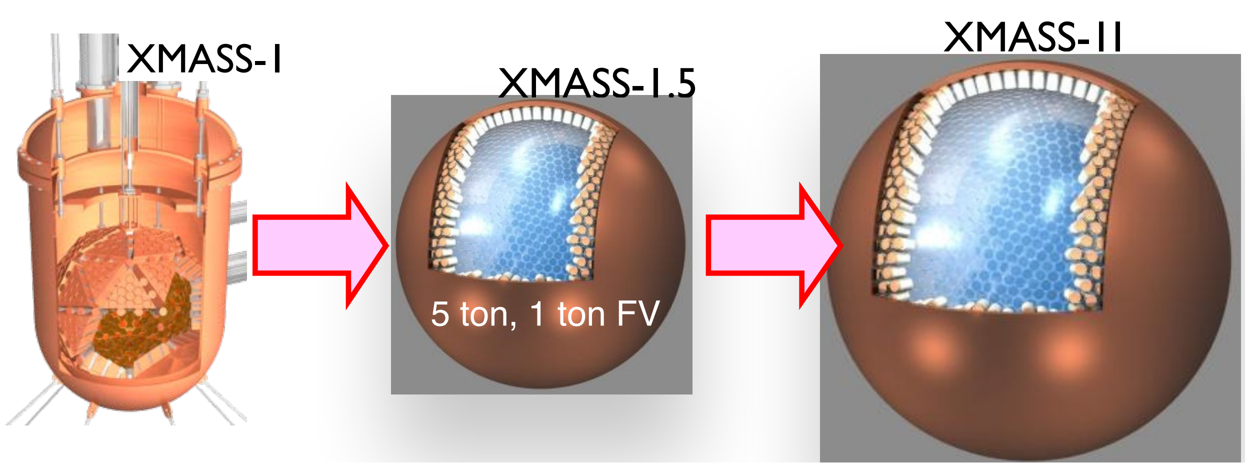
Branching (→) sketched for **electron** recoils

Single phase Xe: XMASS

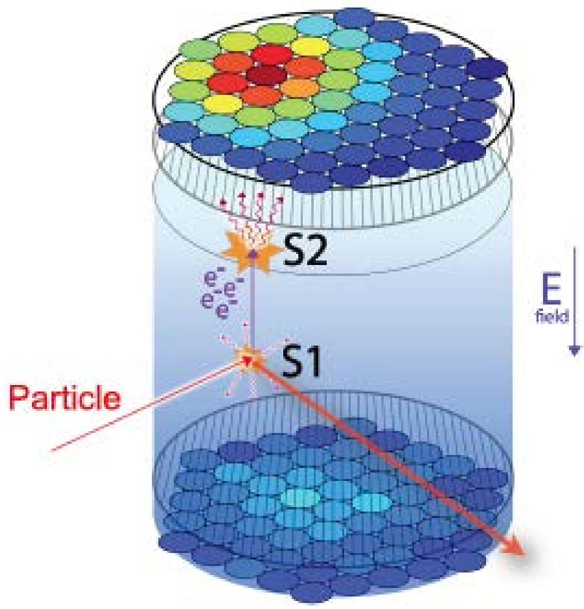
- XMASS-1: 835 kg / 642 PMTs
- Simple, good light collection
  - 14 pe/keVee
- Rayleigh scattering complicates position reconstruction
- Surface Rn-backgrounds crucial
- 40 kg fiducial at 40 keV threshold





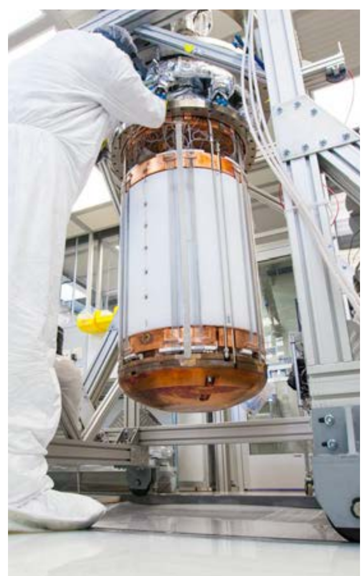


LXe TPC experiments

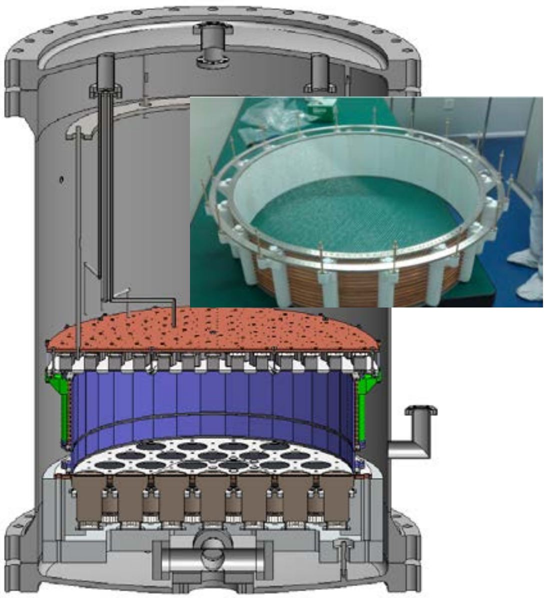


- Long history, and leading DM results
- High quality 3D imaging makes better use of self shielding
- Electron recoils distinguished by their higher amount of charge / light.

XENON-100

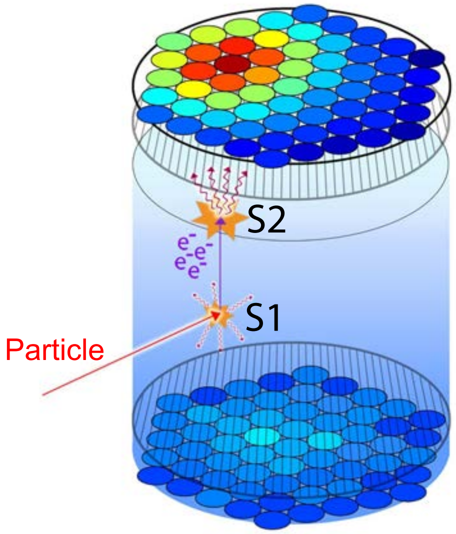


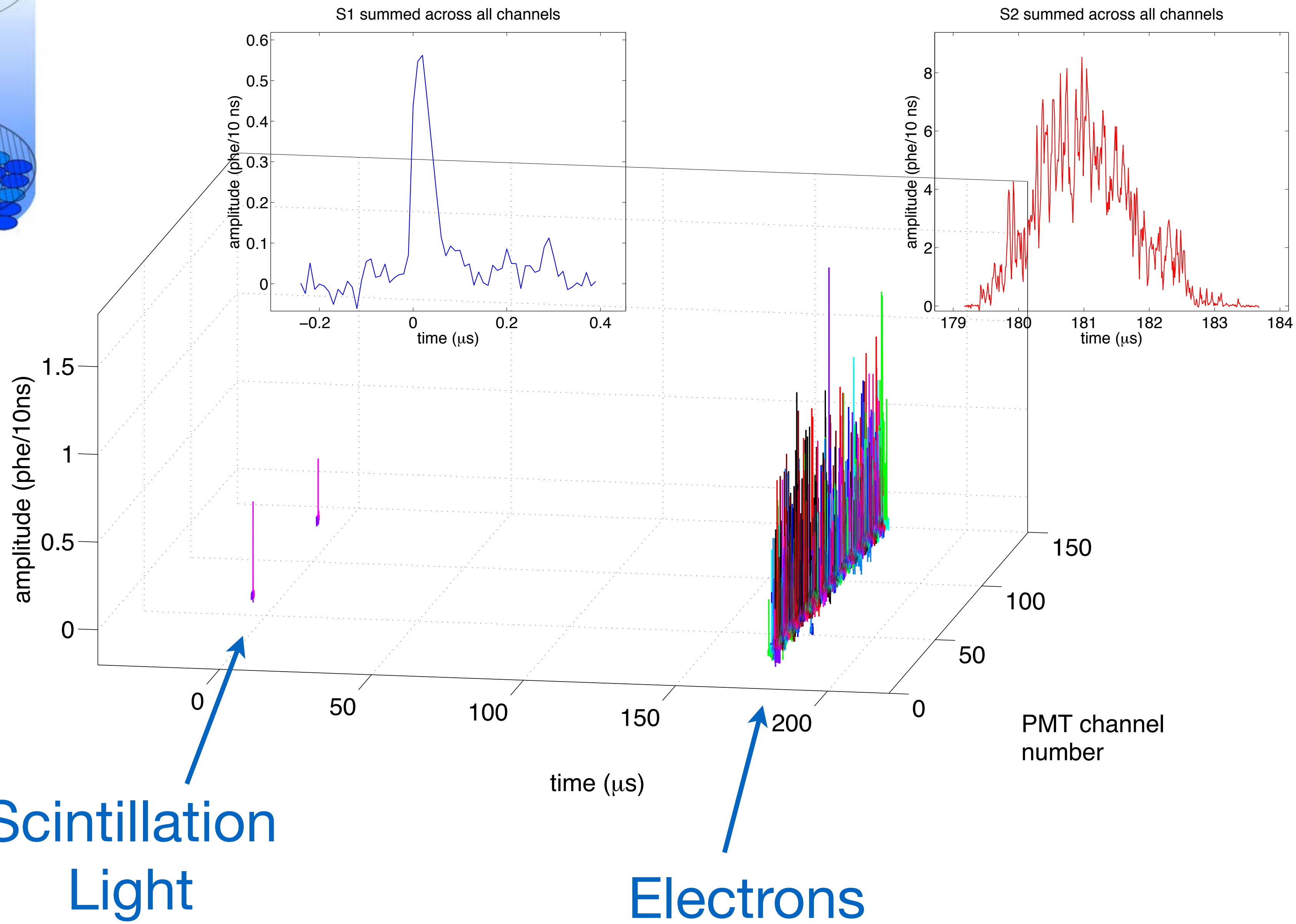
LUX



Panda-X

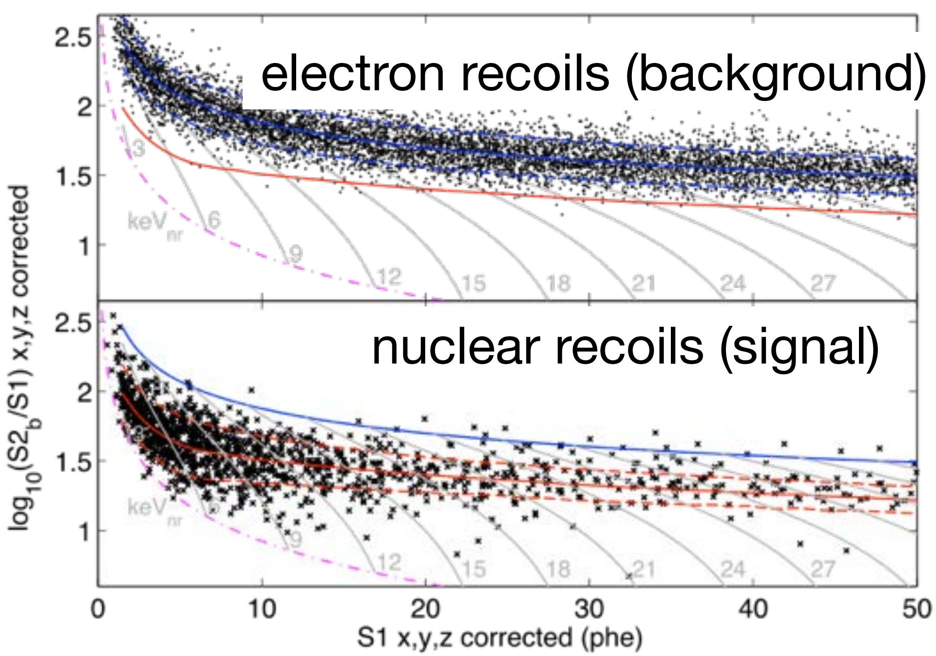
Low energy nuclear recoil



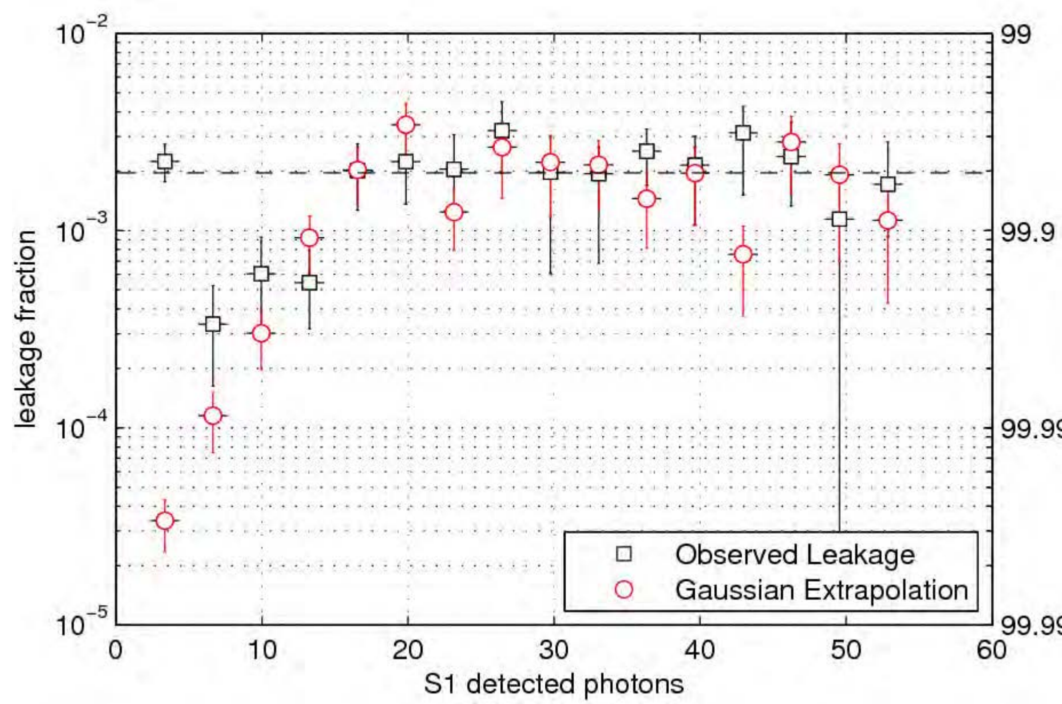


Background discrimination - charge/light

Calibrations

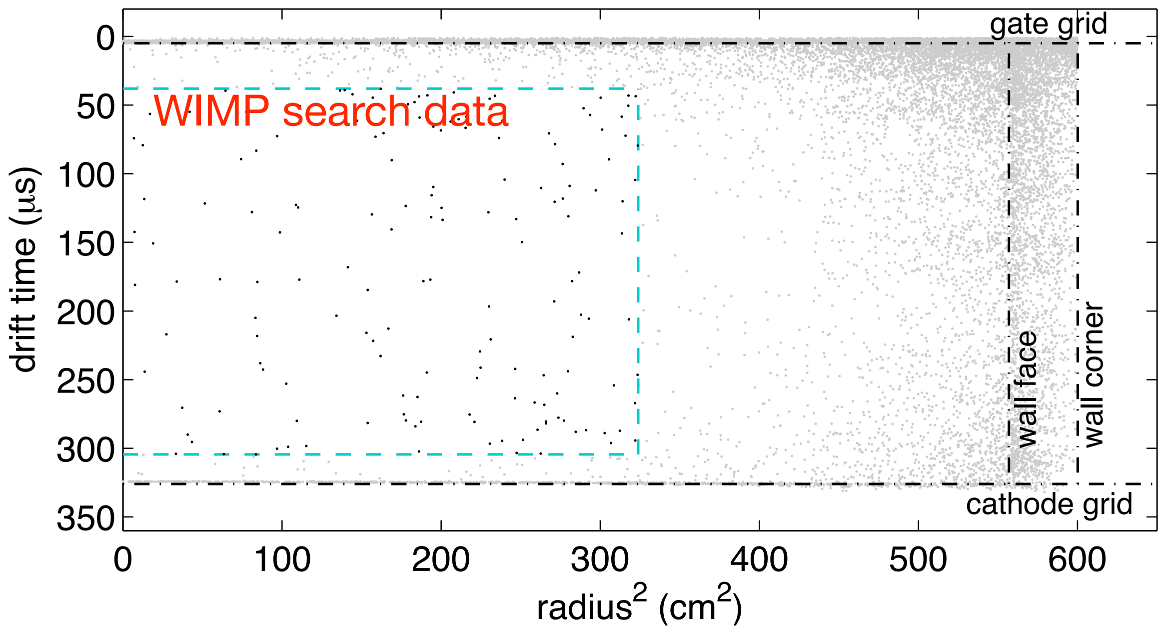


Electron Recoil Rejection



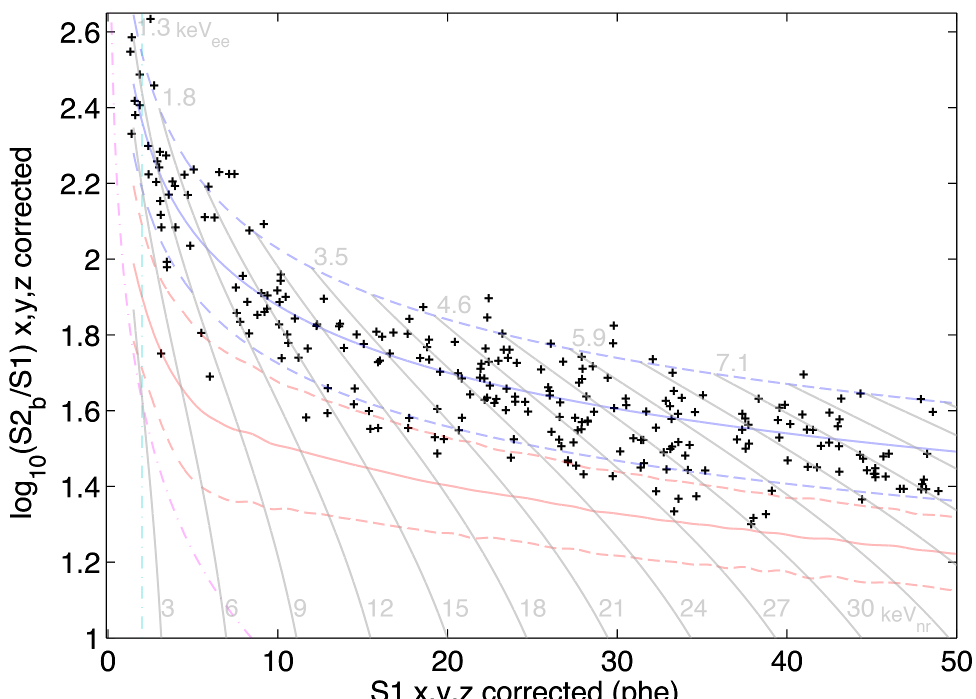
- Extensive calibrations, including *in-situ* ^{83}Kr and tritium (in CH_3T)
- Discrimination of electron recoil backgrounds based on charge/light ("S2/S1") very well measured.

LUX WIMP Search, 85 live-days, 118 kg



Fiducial cut

- *Δx-y:* ~cm
- *Δz: < cm*



Final data

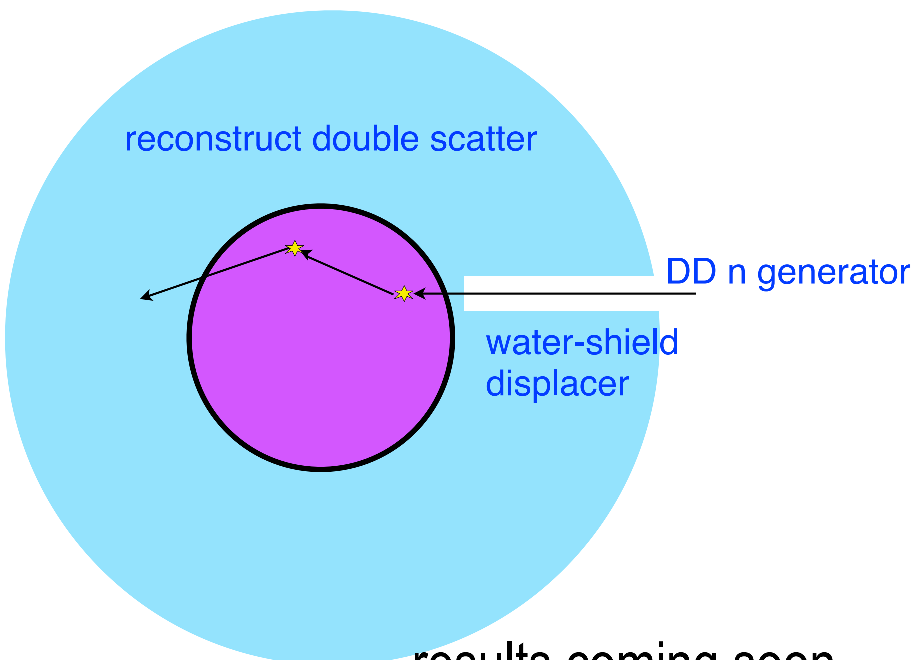
Fit data to combined sig & bkg (^{127}Xe, ^{85}Kr, ^{214}Pb, Compton)

Profile Likelihood Ratio test consistent with all bkg.

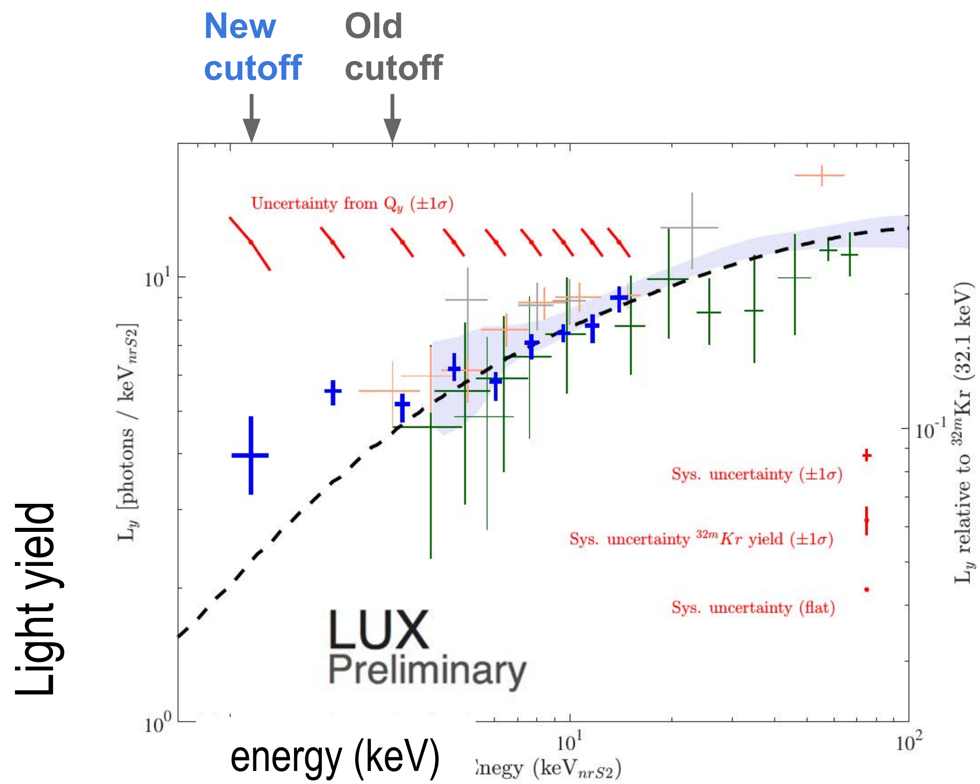
Calibration of Lindhard effect

- Nuclear recoils lose energy to heat, as first calculated by Lindhard
- Theory is approximate, need calibration with neutrons.
- Difficult, especially with compilation of charge + light

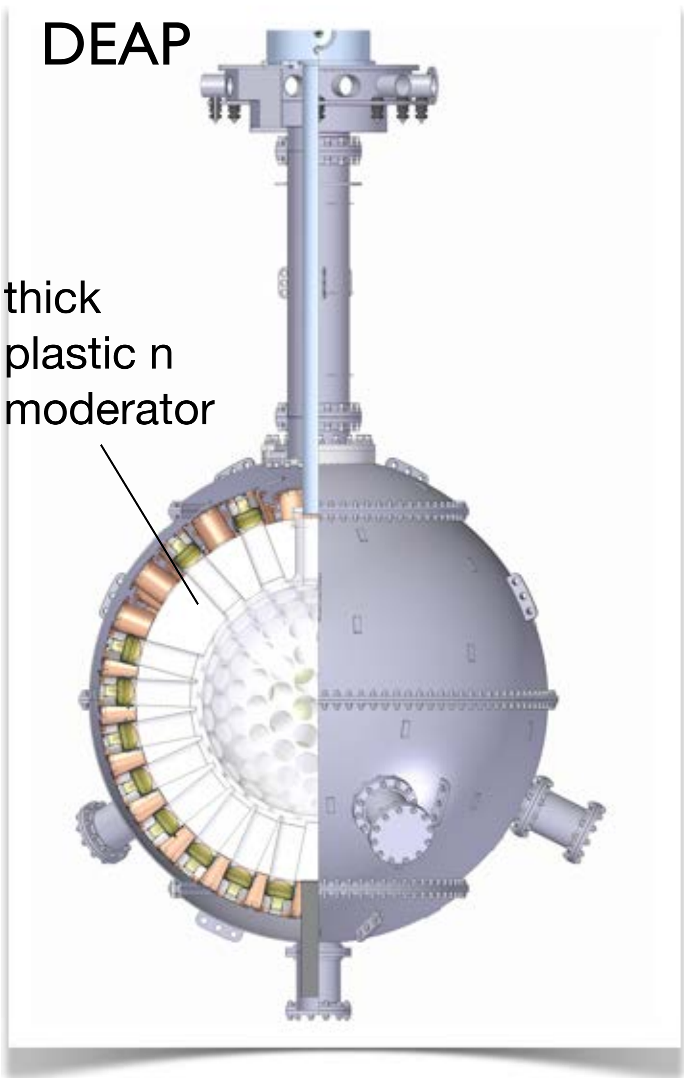
LUX: *in situ* using water tank as collimator



results coming soon

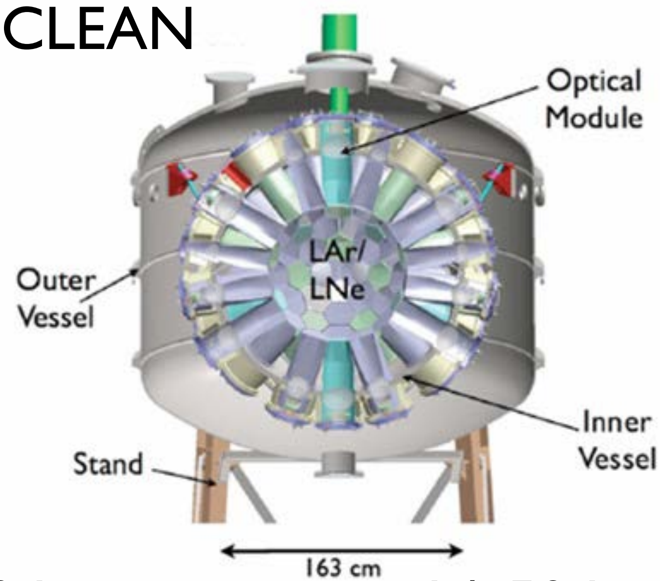


Single Phase Liquid Argon



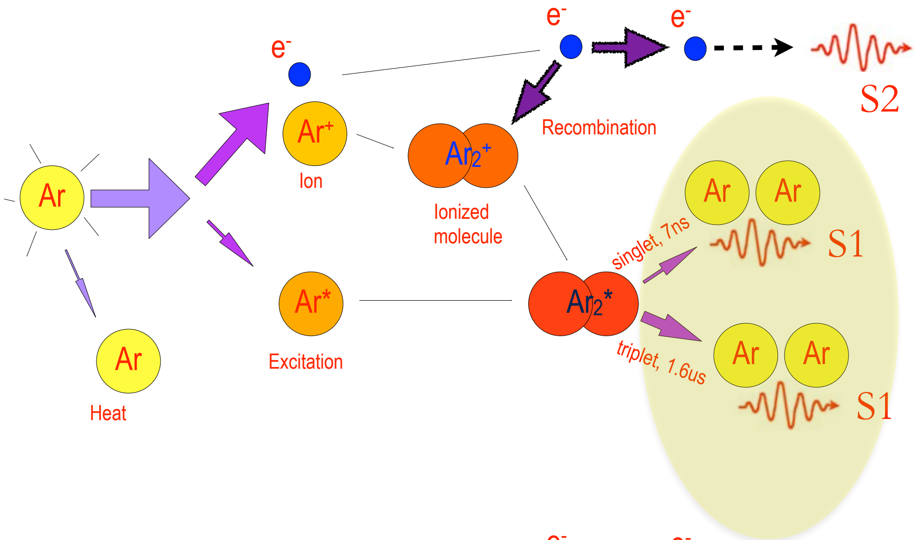
3600 kg instrumented
1000 kg fiducial

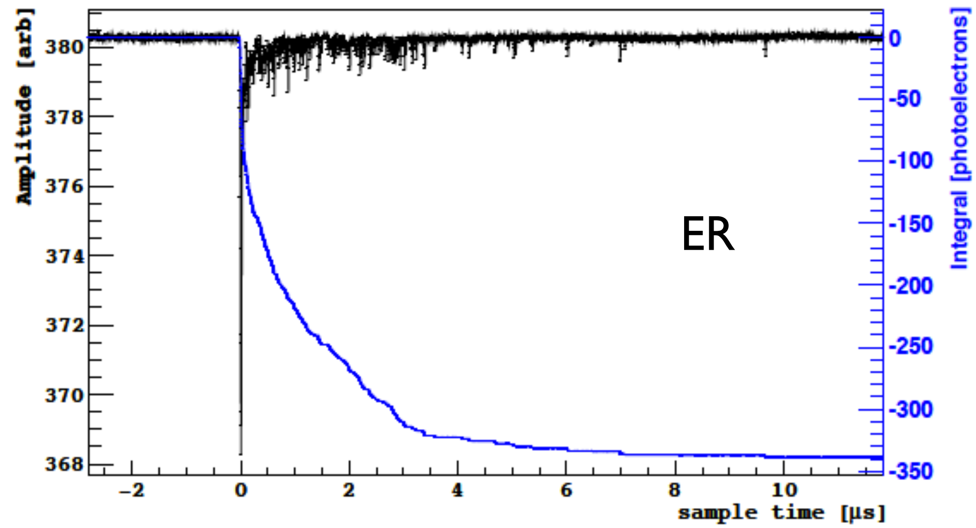
- 128 nm light - requires waveshifter (TPB)
- Intrinsic background: ^{39}Ar, ~600 keV endpoint beta
- Significant pulse shape discrimination
- Ar inexpensive

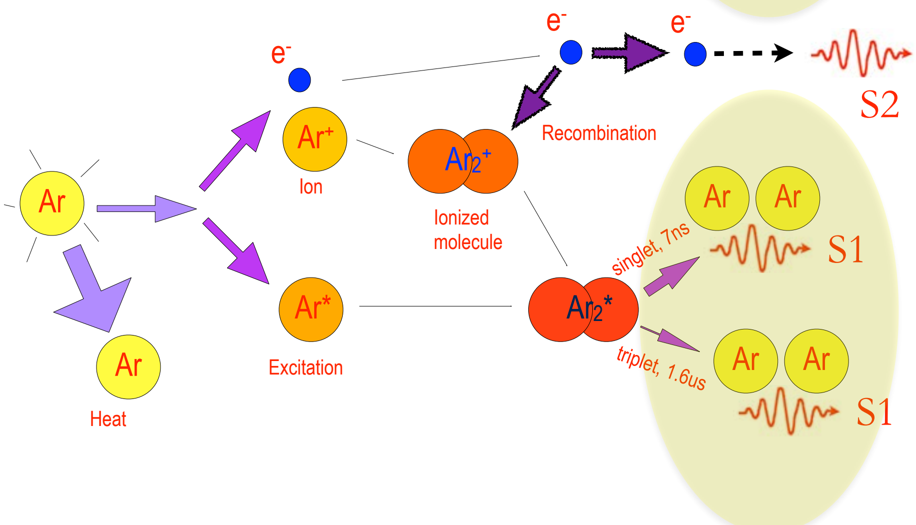


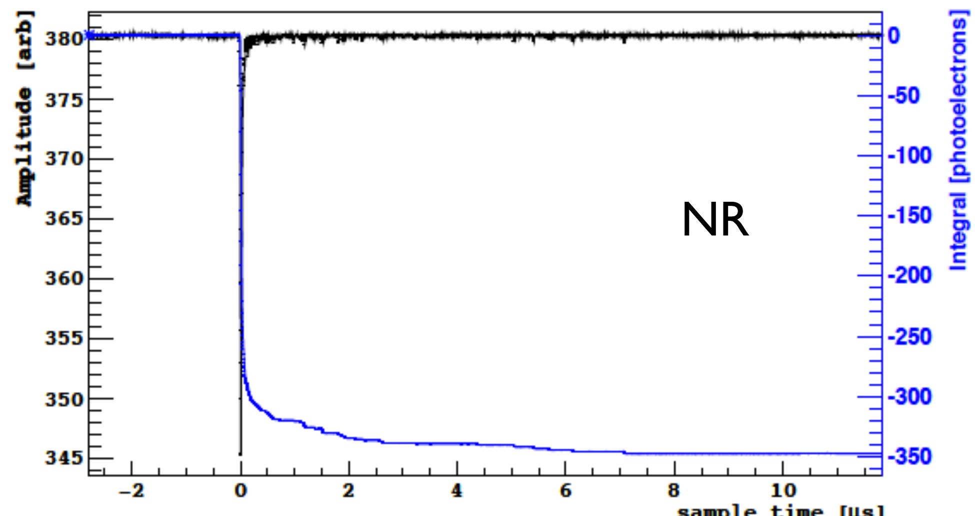
500 kg instrumented / 150 kg fiducial

Pulse Shape Discrimination (PSD) in LAR



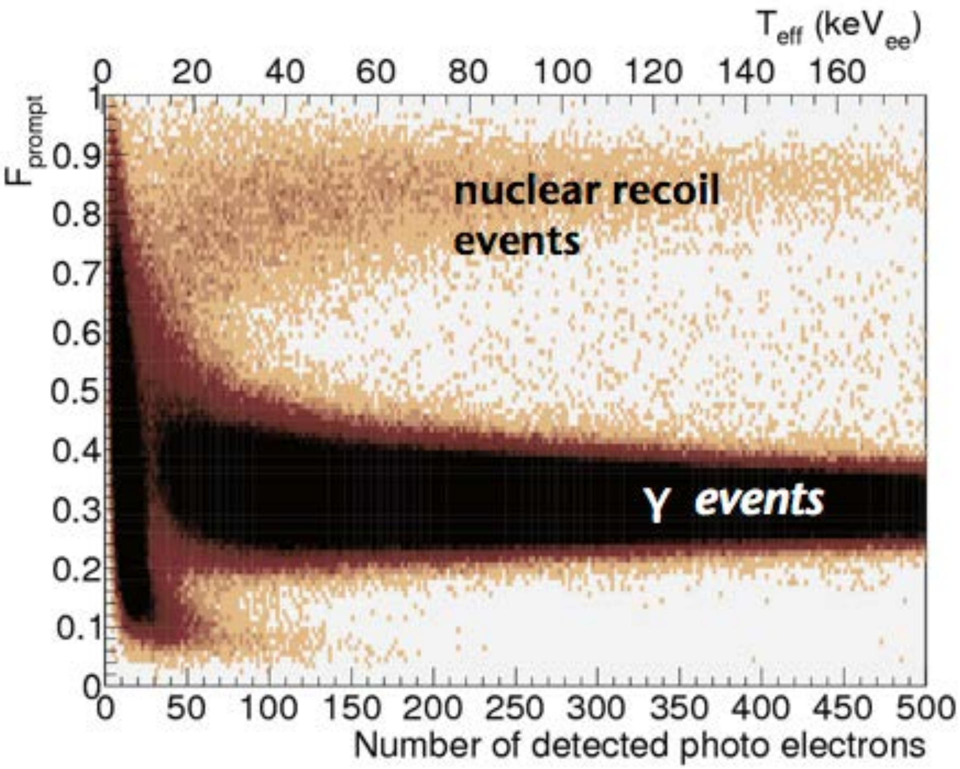


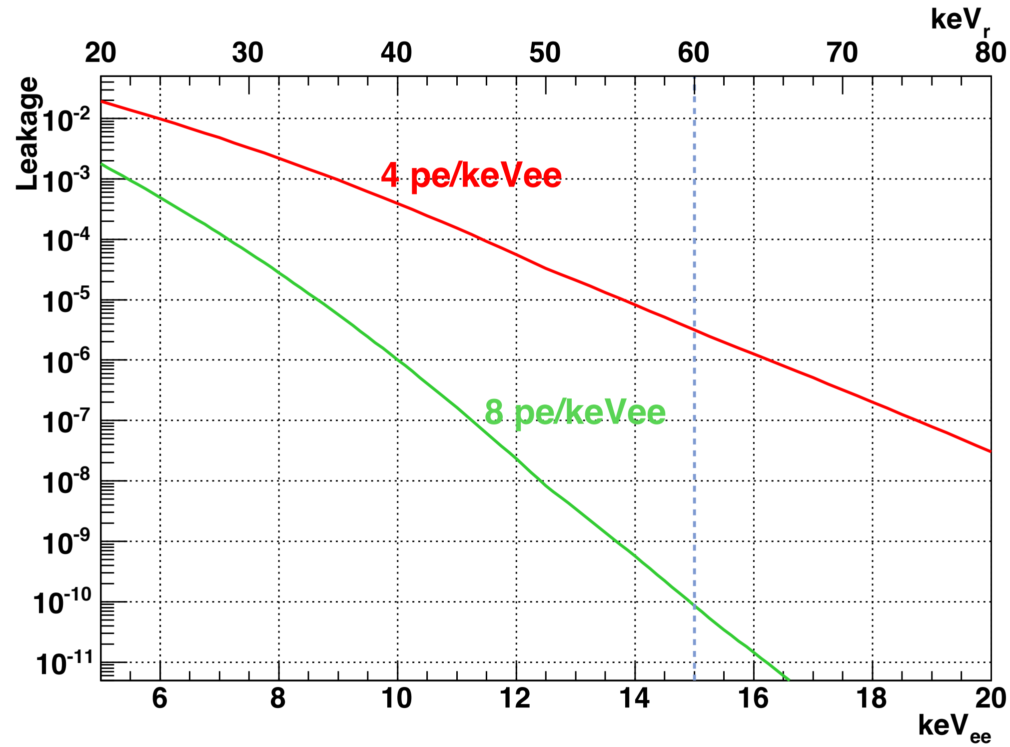




(DarkSide 50 data)

PSD demonstrated in DEAP-1

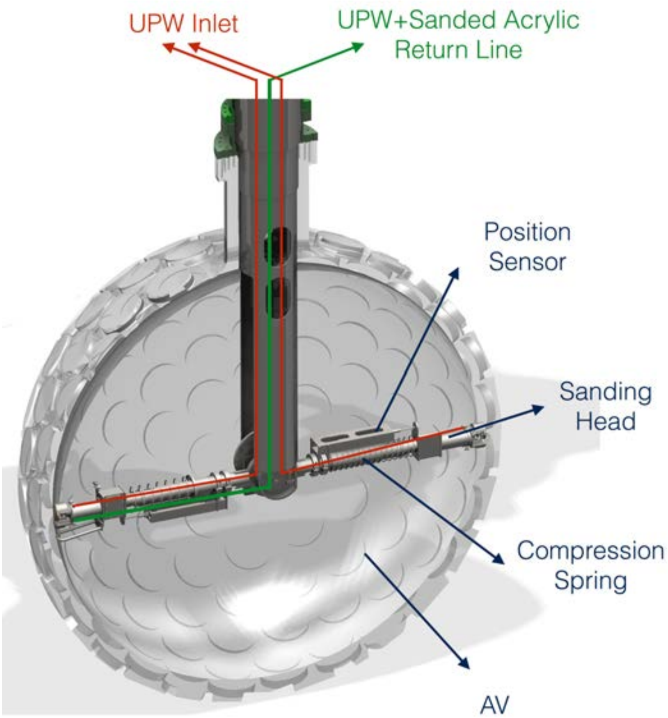




- Needed > ~10^8 discrimination achieved
- Highly sensitive to light collection / energy threshold

Surface backgrounds

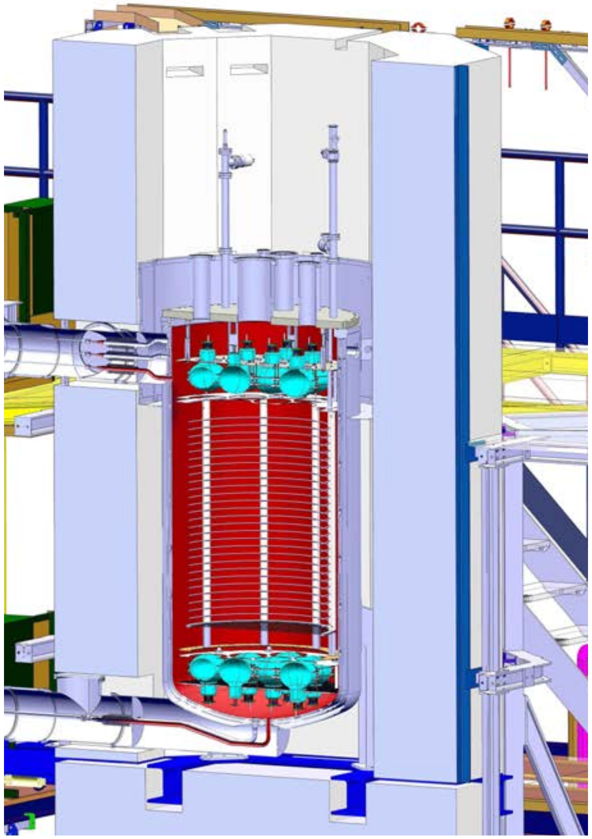
- Nuclear recoil of ^{206}Pb following Rn-daughter ^{210}Po decay.
  - Significant background also in XMASS
- Very difficult to eliminate Rn exposure during assembly
- Interior of surface mechanically polished, waveshifter applied in inert atmosphere



2-Phase Liquid Argon TPCs

- Combine electron recoil discrimination from PSD and charge/light
- Accurate 3D imaging

DarkSide



ArDM

Underground Ar

- Standard ^{39}Ar - 1 kHz / ton, $t_{1/2}$ = 269 yr
  - S1: ~μsec time window.
  - S2+S1: ~msec drift times.
  - 39Ar: 269 years.

- Underground ancient Ar
  - Challenge: ^{39}Ar generation in crust rock with U, Th, K.

- Ar from CO2 mine in Colorado
  - Cocktail of gasses
  - Processing on site
  - Post-processing at FNAL

UAr VPSA extraction facility, Cortez CO

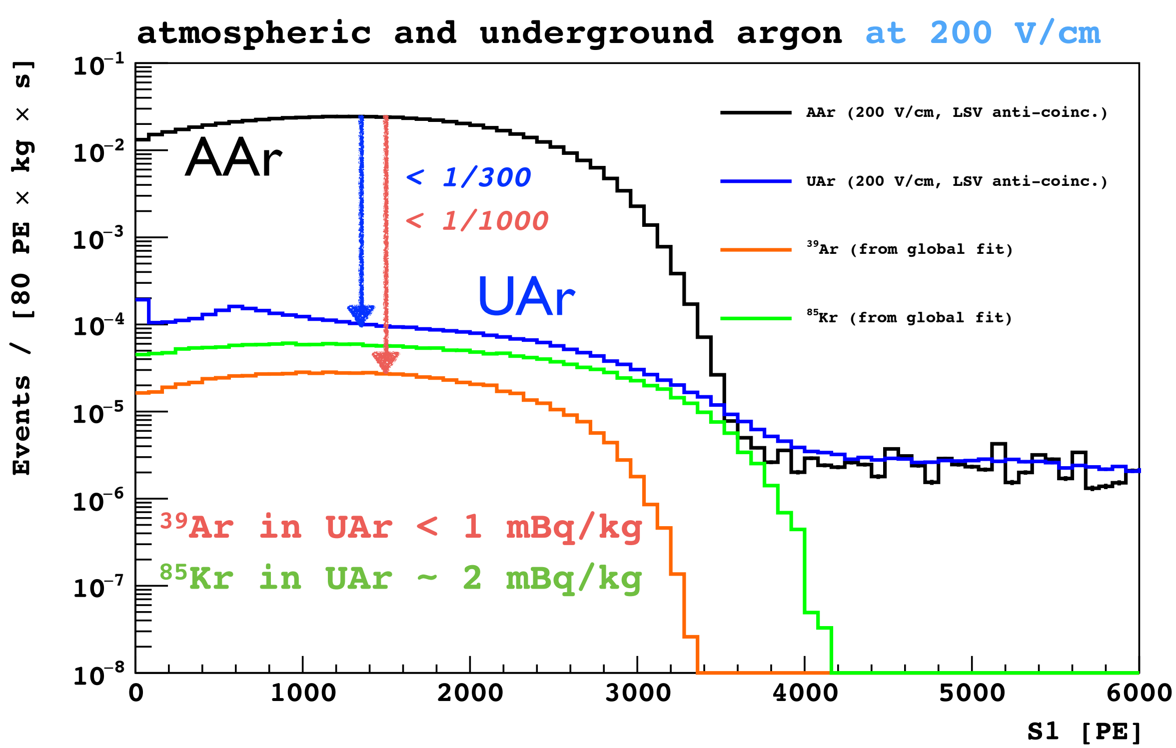
Operated locally by technician Gary Forster – Managed by H. Back

Andrea Pocar - UMass Berkeley Workshop on Dark Matter Detection - LBL -

FNAL distillation column

DarkSide-50

- 50 kg fiducial. In Gran Sasso
- Outer scintillator - neutron veto
  - Relaxed gamma background requirements, but neutrons still a challenge.
- Key result with underground Ar: 1200x suppression of ^{39}Ar
  - 300x background reduction - some ^{85}Kr
- Measurement of charge/light discrimination to come



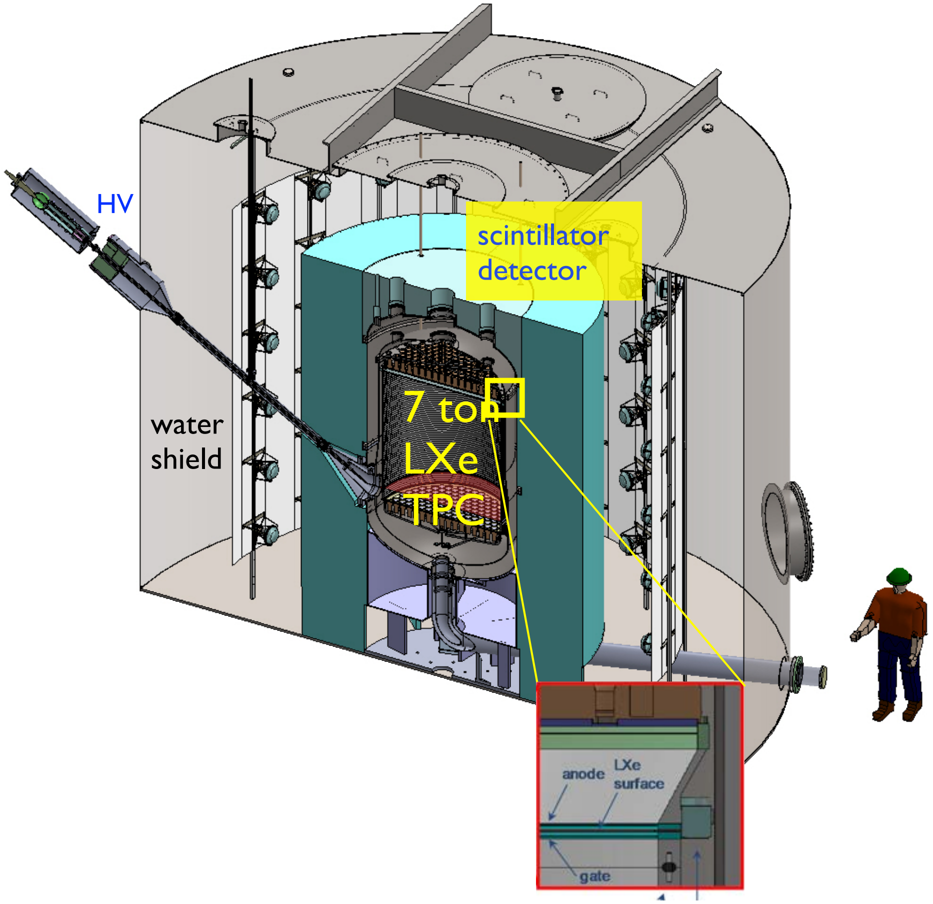
Two Phase Xe: next experiments

XENON1T / nT

- 3.3 tons LXe / 2.0 tons active
- Building and commissioning well underway
- Start of science expected 2015
- Expand to 7 tons LXe - replace inner vessel and TPC

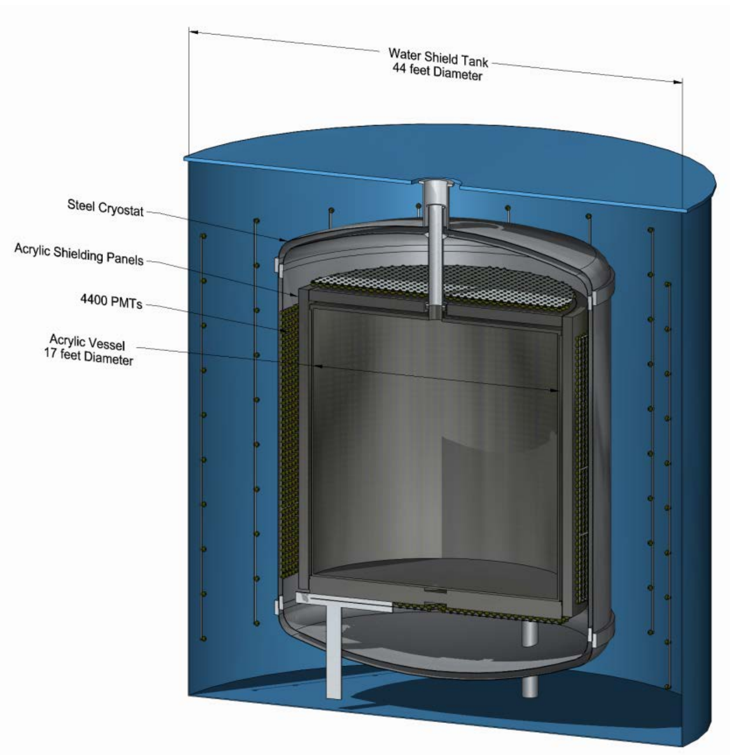
LUX / ZEPLIN

- 10 tons total, 5.6 tons fiducial
- Outer detector system
- Start of science expected end 2018

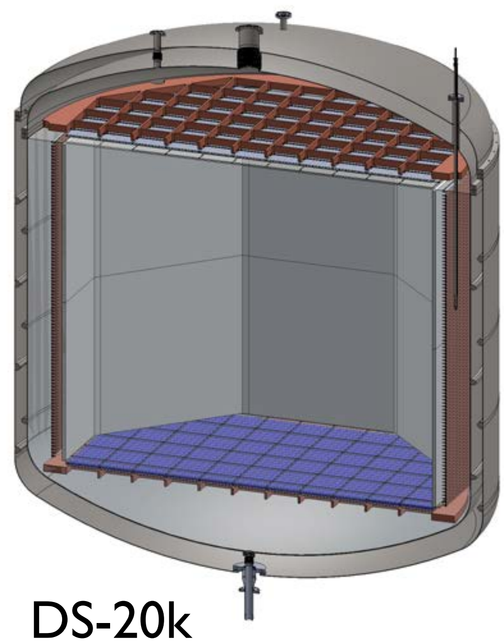


Beyond G2

- LAr: DEAP single phase
- 50-ton fiducial



- LAr: DarkSide 20K - 30 ton total, 20 ton fiducial
- ARGO: 300 tons
- Both with depleted Ar

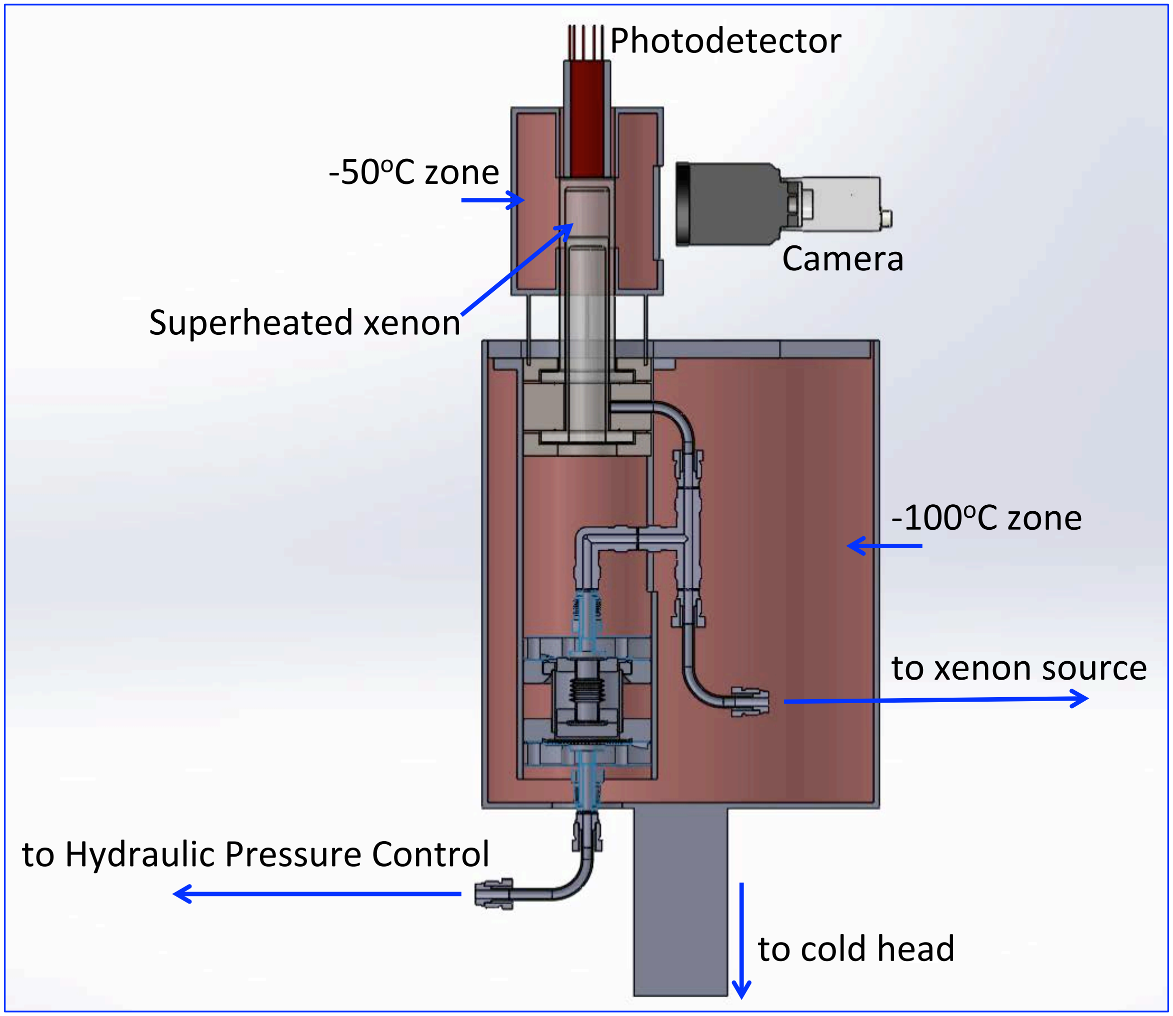


- DARWIN
- Design study for 30-50 tons LXe

A Scintillating Xenon Bubble Chamber

(C.E. Dahl, M. Szydagis)

- All the perks of a bubble chamber
  - 10^{-10} ER insensitivity
  - Easy 3D recon (no E-field req'd)
- With scintillation light for energy scale
  - Eliminate alpha-decay backgrounds

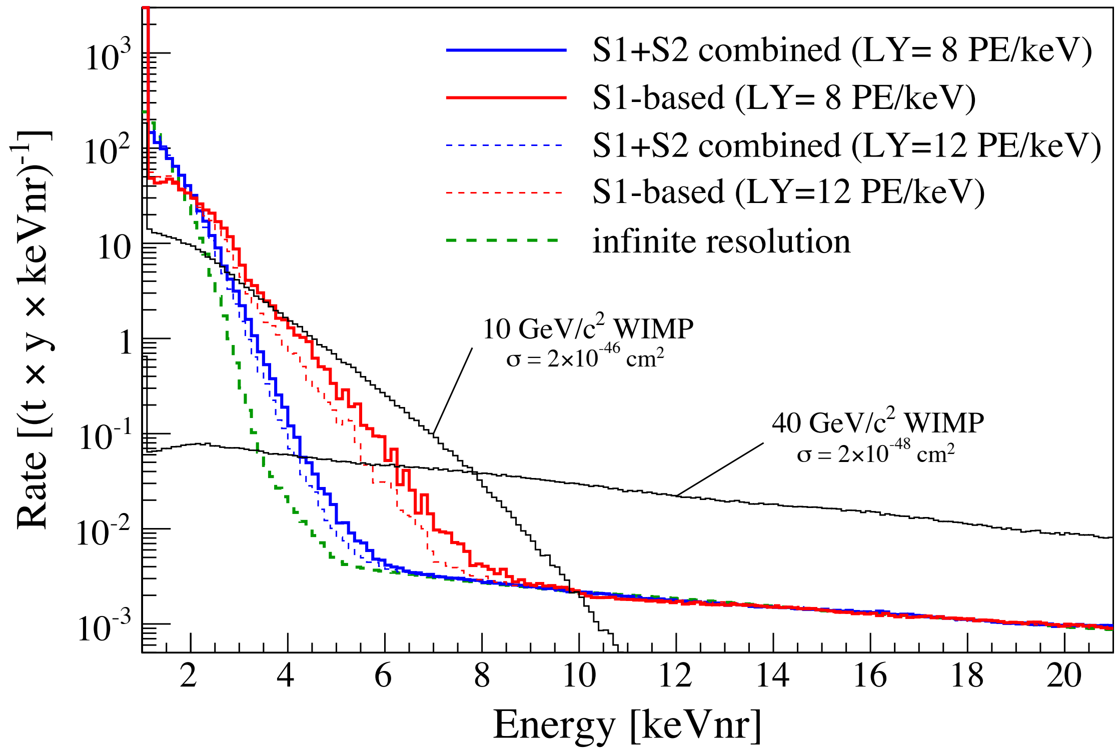


Feb 2015, Conceptual design

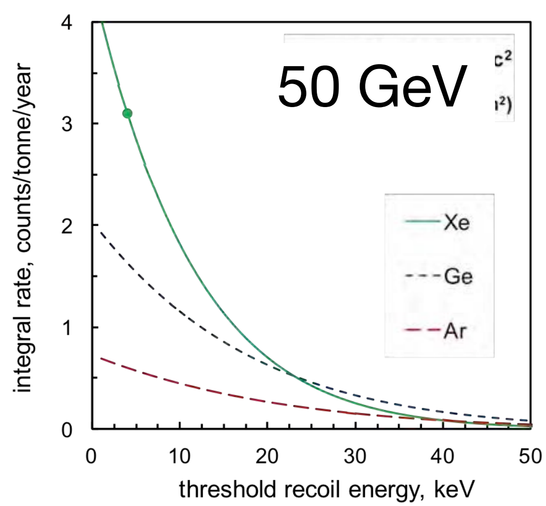
Exploring the neutrino floor

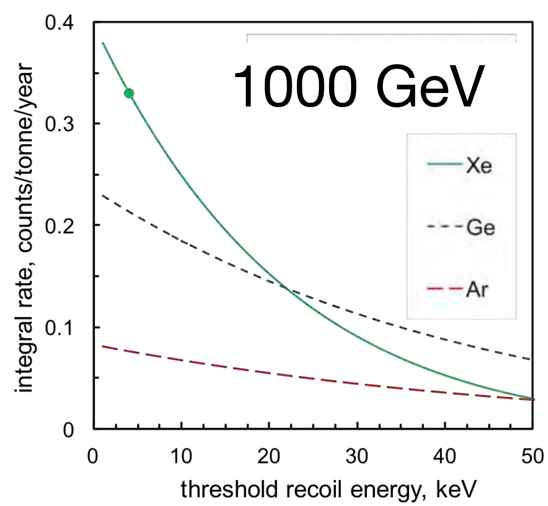
DARWIN - 1506.08309

- LXe - 50 tons, 300 t-yr (DARWIN)
  - 3 CNNS events
  - Limited sensitivity improvements after that
- LAr: ARGO - 300 tons, similar reach

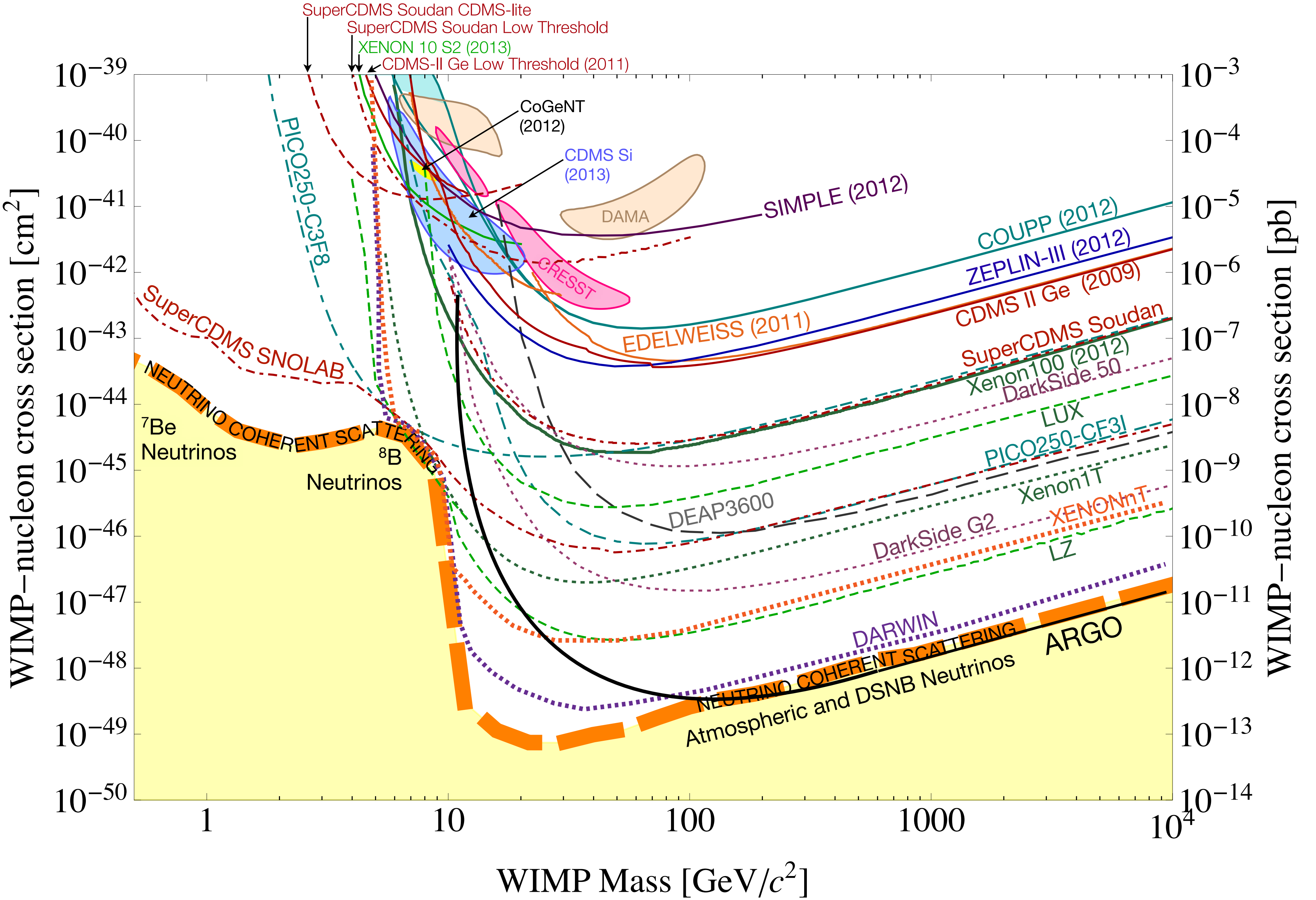


WIMP sensitivity: Xe, Ge, Ar





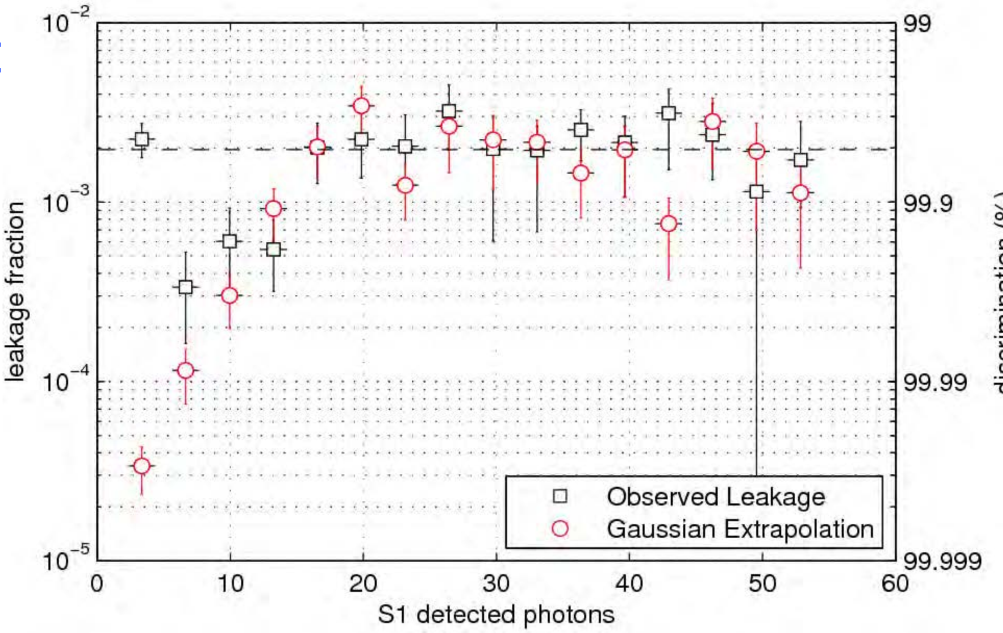
Projected sensitivity



Challenges - S2/S1 discrmination

- Xe
  - LZ projection:
    - 324 raw ER events: pp solar *ν* (271) + ^{136}Xe 2*ν* *ββ* decay (54)
    - 1.6 after assumed 99.5% discrimination (50% acceptance)
  - Want > 99.9% for 30-50 ton experiment
  - ER discrimination: no consensus
    - ZEPLIN III (4 kV/cm drift field): 99.99%
    - Claims above 99.9% at lower drift field (K. Ni, at Astroparticle 2014)
  - Improves with light collection
  - Appears to improve with higher drift
- Ar
  - Need study at low energy
  - DarkSide results should inform us

LUX ER Discrimination



Challenges - High Voltage

- LAr TPCs for beam neutrinos routinely achieve > 100 kV in LAr
- Dark Matter community has not fared as well
  - Detector limited to near ~10 kV so far
  - Studies in LXe have not seen fundamental limits.
    - On ~cm^2 surfaces and small grids: stable 400 kV/cm
    - Charge multiplication > ~725 kV/cm, light generation > 410 kV/cm (Aprile: 1408.6206)
  - 100 kV achieved in test system for XENON1T
- Needs careful development work

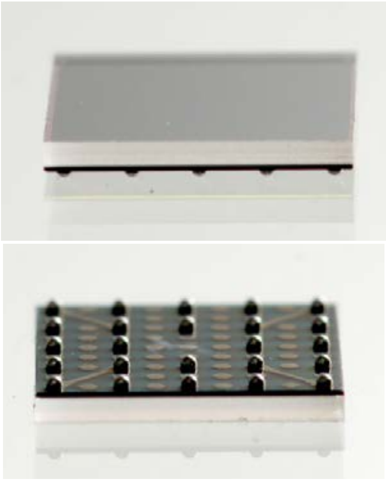
LZ System test facility at SLAC

- Primary goal is test of high voltage systems in LZ
- IR2 - site of the TPC experiment, BABAR
- High voltage feedthrough - Yale/UCB - 200 kV

Challenges - Light Collection

- SiPM - higher light collection, especially for LAr
  - Single photon counting with high QE; dark current at 80K looks manageable for m2 arrays
  - PSD exponentially sensitive to light collection
  - Much less radioactive than PMTs
  - For LXe, need waveshifter - purity concern
- LAr - optimizing all aspects of waveshifter
  - Reflectivity / transparency for shifted light
- Reflective materials
  - LXe: PTFE is unreasonably reflective. Why? Is it 97%? 99%?
    - Difference matters
    - Are different PTFEs different?
  - More options with waveshifted light - Vikuiti film - 99.%
  - Grid wires. Direct tradeoff between transparency and electric field
- Lower background PMTs.
  - Current tubes very good, but some glass/ceramic remains

ArDM



Isotopic Separation

- Ar - remove ^{39}Ar
  - DarkSide considering cryogenic distillation
- Xe
  - Separating ^{136}Xe removes background for full solar neutrino spectrum
  - Enriched ^{136}Xe allows $\beta\beta$ decay
  - Low / high mass split gives spin / non-spin (odd n) targets

Conclusions

- Liquid noble detector using Xe and Ar have opened and era of unprecedented dark matter sensitivity above ~10 GeV
- Absent directional detectors, our best hope is to just look under the rug on the neutrino floor
- R&D is needed to determine the optimal technology to achieve this